DYNAMICS OF INNOVATION OF BIOFUEL ETHANOL.

THREE DECADES OF EXPERIENCE IN THE U.S. AND IN BRAZIL

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Elena M. Berger

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Approved by:

Dr. Susan Cozzens, Advisor
School of Public Policy
Georgia Institute of Technology

Dr. Kirk Bowman
School of International Affairs
Georgia Institute of Technology

Dr. Marilyn Brown
School of Public Policy
Georgia Institute of Technology

Dr. Frank Laird
School of International Studies
University of Denver

Dr. Valerie Thomas
College of Industrial and Systems Engineering;
School of Public Policy
Georgia Institute of Technology

Date Approved: November 12, 2010

To my children Cesar, Daniel, and Melissa

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SUMMARY

This dissertation draws on the burgeoning field of innovation of low carbon technologies. Using the functions of innovation systems, this study explores the process of innovation of biofuel ethanol in the U.S. and in Brazil. It uses “process theory” to build a narrative of historical events that represent the innovation trajectory of ethanol biofuel in the U.S. and in Brazil over a period of thirty years. The data is drawn from newspaper articles from the New York Times, Washington Post, and O Estado de Sao Paulo published between 1975 and 2008. Results of this research confirm findings published previously that innovation performs better when the main actors in the innovation process act under clear and well defined policy targets, and when the innovation environment contributes to building positive expectations about the technology. The empirical findings build upon the literature and validate early claims that the alignment of goals between technology producers and users is an inducer of innovation. Moreover, the analysis presented shows that by developing new capabilities, technology users in the downstream market broaden the innovation environment and facilitate the adoption of the emerging technology by new users and markets. For example, the automobile sector has been participating actively in the ethanol technological innovation system in Brazil, facilitating the innovation flow between upstream and the downstream market. This has not been the case in the U.S., where the automobile sector has not found incentives to participate in the ethanol technological innovation systems.

CHAPTER 1

INTRODUCTION

1.1 Transportation sector: the oil drive

Our over-reliance on fossil fuels will lead the world to an unsustainable path of energy consumption, greenhouse gas (GHG) emissions, and climate change (IEA, 2009a; NAS, 2009; Walter, Rosillo-Calle, Dolzan, Piacente, & da Cunha, 2008). Under business as usual, fossil fuels will account for the largest increase in energy use in the next twenty years, with the transportation sector claiming 97% of the growth during this period (IEA, 2009a, 2009b).

Developed economies claim large amounts of fuels for transportation, but the main factors pushing fuel consumption worldwide are population growth and higher vehicle ownership in emerging economies (IEA, 2009a). Demand for fuel will be driven not only by American and European automobile markets, but by a growing proportion of new consumers buying cars for the first time in China, Russia and India over the next decades (Figure 1).

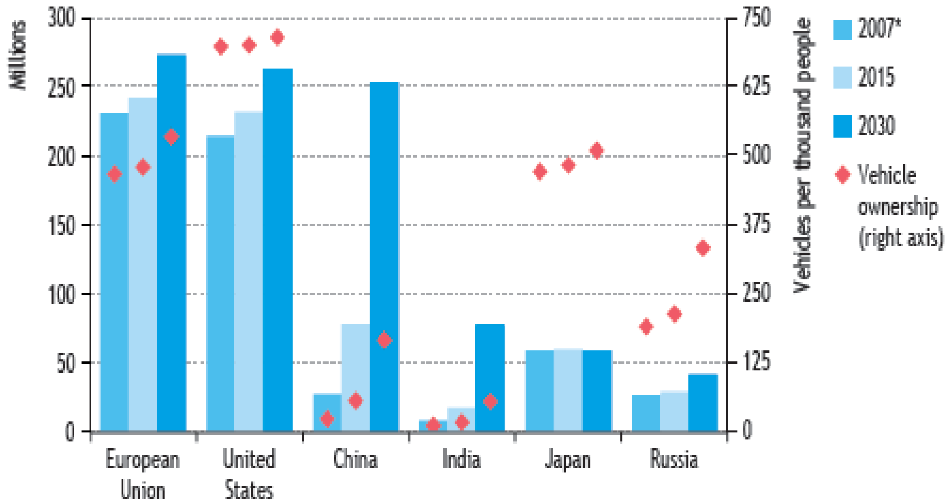

Figure 1: From the IEA World Energy Outlook 2009: Passenger light duty vehicle fleet and vehicle ownership per capita

In the United States, transportation accounts for one third of energy related greenhouse gas (GHG) emissions (AEO2010), with Americans consuming approximately 14 million barrels of oil per day, 9 million of which is used to power a fleet of more than 200 million light duty vehicles (Earley & Mc Keown, 2009; NAS, 2009). The transportation sector accounts for 28%[1] of the national energy consumption, and supply is mostly dependent (98%) on oil (US DOE, 2009). There has been a growing sense that technological innovations[2] alongside with environmental policies are critical to help the U.S. reverse this scenario (Alic, Mowery, & Rubin, 2003; Holdren, 2006).

The U.S. growing vulnerability on energy security and climate change has justified public policies promoting research, development and the adoption of low carbon and sustainable[3] technologies to replace fossil fuels[4] . Biofuels, which are alternative

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[1] From which highway vehicle travel accounts for 85%.
[2] http://www.americanenergyinnovation.org/
[3] Sustainable technologies emit lower levels of GHG, they are economically affordable, and they use resources that can be replaced without harming social and environmental systems (NSB 2009).

fuels derived from biomass (non-fossil, organic, renewable), are considered one of the short term solutions available to replace part of America's fossil fuel demand for transports (EERE/Biomass, 2009; Holdren, 2006). Like other low carbon technologies, biofuels face tough competition against fossil fuels. These alternative fuels still struggle to develop within a system that does not enable the adoption of routines or rules that are conducive to technological progress, or high market penetration of low carbon technologies.

Given the potential contribution of biofuels to replace part of the growing demand of fossil fuels, the study of the innovation of biofuels deserves particular attention. Biofuels compete with an incumbent – fossil fuels like gasoline and diesel - that dominates the market, and is embedded within an innovation environment that has not yet developed the mechanisms to enable the full development and market penetration of clean technologies (Timothy Foxon, Kohler, & Neuhoff, 2008a; Marko P. Hekkert & Negro, 2009; Suurs & Hekkert, 2009). In this sense, identifying the barriers and inducers of the process of development, diffusion, and adoption of biofuels is an important topic for research.

Innovation is a process that enables and promotes the creation, diffusion, and adoption of new technologies or new processes (Edquist, 2005; Kline & Rosemberg, 1986; B.A. Lundvall, 2007). The systemic view of innovation argues that the process of innovation is long, complex, and it does not happen in isolation (Edquist, 2005). Drawing on theories of innovation, this study explores the process of innovation of biofuels examining historical events that represent the innovation trajectory of biofuels in the U.S. and Brazil – the two largest producers - over a period of thirty years. The study analyzes

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[4] Energy Secretary Steven Chu emphasized the importance of science and technology and innovation to promote renewable energy and efficiency at the Copenhagen Climate Conference in December 2009 (www.energy.gov/news/8394.htm)

chronological events around ethanol in the U.S. and Brazil using a set of quantitative and qualitative analytical methods. It uses “process theory” (Van de Ven & Poole, 2000) to build a sequence of events from newspaper articles published between 1975 and 2008.

The dissertation confirms results reported previously that innovation performs better when the main actors in the innovation process act under clear and well defined policy targets, and when the innovation environment contributes to build positive expectations about the technology. This result is consistent with the assumption that: 1) actors within the innovation environment operate under uncertainty and bounded rationality; and 2) they pursue searching, interacting, and learning activities to innovate – that is, to develop, diffuse, and adopt new knowledge and technologies (B. A. Lundvall, 2007). The empirical findings also validate early claims that the alignment of goals between technology producers and users is an inducer of innovation.

Building on the literature of innovation systems, this study proposes and tests empirically an additional function of innovation – capability building in the downstream market. This concept suggests that in some cases, innovation in the downstream market creates conditions to accelerate innovation in the upstream market. The case of the rebound of the ethanol industry in Brazil following the development of the flex-fuel vehicle capable of running on ethanol, gasoline, or any mixture of the two fuels offers empirical support for this claim. The study shows that the development of flex fuel vehicles in Brazil took advantage of and built upon the knowledge acquired during the early years of the National Alcohol Program, when Brazilians drove cars with engines tuned and adapted for ethanol.

1.2 The dynamics of innovation of biofuel ethanol

This study focuses on biofuel ethanol, rather than other major biofuel, biodiesel, because ethanol has the largest production volume in the world, with U.S. and Brazil sharing approximately 85% of global output in 2009 (RFA, 2010). Moreover, ethanol competes with gasoline and is compatible with combustion engines, the technology used in most light duty vehicles in the U.S. and Brazil.

Both Brazil and the U.S. started industrial production and mass commercialization of ethanol during the 1970s, in reaction to the Arab Oil Embargo. As a sugar producer since colonial times, Brazil developed ethanol capacity using sugarcane as a feedstock. Leader and largest exporter of corn, the U.S. capacity is 99% derived from corn-based ethanol. These two feedstocks have different costs and require different conversion processes to ethanol. Despite the difference in process, both products serve the market of combustion engines for the transportation sector, and compete directly with gasoline. Studying the innovation trajectory of ethanol in the United States and Brazil offers the opportunity to understand two different processes with different interplay of factors leading to different outcomes of innovation in ethanol.

In this study, low carbon technologies relate to technologies that have been developed with the goal of decreasing carbon related gas emissions into the atmosphere. They include, but are not limited to, renewable energy technologies such as wind, solar, biomass, geothermal, fuel cell, hydrogen, and others; coal with carbon sequestration; and energy efficiency technologies. Throughout this dissertation, the term “low carbon technology” may be used interchangeably with “clean energy”, or “green energy” to characterize alternatives to fossil fuel or carbon-based technologies.

1.3 The two cases

Studying the innovation of ethanol in the U.S. is useful, because it helps understand how a decade of strong investments in R&D, and long term mandates and financial and fiscal incentives has not delivered a sustained market penetration of ethanol in transportation. The U.S. started its ethanol industry after the 1973 Arab Oil Embargo by producing gasohol, a 10% blend of corn-based ethanol and gasoline. Strong government commitment towards high targets of ethanol began after 2000. The Energy Policy Act of 2005 established the goal of using 9 billion gallons of biofuels in 2008. The Energy Independency and Security Act of 2007 (EISA 2007) expanded the mandate of biofuels and established the goal of consuming 36 billion gallons until the year 2022 (Yacobucci & Bracmort, 2009). Stimulated by tax breaks and mandates, the U.S. became the world's largest ethanol producer (51% of the world production) in 2006.

Americans have also been the leaders in R&D investments in advanced technologies that process biomass (from cellulose and non edible) for ethanol production ((S&T)2ConsultantsInc., 2009; EERE/Biomass, 2009; IEA, 2009a; Kamis & Joshi, 2008)); American firms, academic, and research institutions have been the world first in scientific publications and patent applications in ethanol-related technologies (Kamis & Joshi, 2008). And yet, despite American primacy in science and technology in biofuels (Berger & Cozzens, 2009), and strong government incentives for large production, there is still low penetration of biofuels in the gasoline market (approximately 5%). Around 99% of ethanol is used as oxygenate or additive, in blends of 10% with gasoline (US DOE, 2009). Currently, the U.S. has approximately 8 million flex fuels vehicles (less than 4% of its car fleet) capable of using E85, a blend of 85% ethanol and 15% gasoline, but most of them run on 100% gasoline, because there is not the necessary infrastructure to distribute ethanol fuel around the country (GAO, 2009; RFA, 2010). Despite the strong technology push and long term government market incentives, ethanol has been a complement, and not a substitute for gasoline in the U.S. The Environmental Protection Agency (EPA) has not approved ethanol blends above 10%, and industrial growth has been hampered by the blend wall, or the limited size (10% of the gasoline market) of the blender market[5] .

[5] Ethanol installed capacity is approaching 10% of the gasoline market.

The case of Brazil is useful to explore a process of innovation that culminated into a successful and self-reinforcing innovation system. Like the U.S., Brazil began its ethanol innovation process in earnest following the 1973 Arab Oil Embargo. At that time, Brazil's military government addressed the country's dependence on oil (80% of oil demand was imported) and financial stress, by putting together a national plan to produce and distribute ethanol from sugarcane. Like the U.S., Brazil focused its innovation process by investing in science and technology in the agricultural and industrial sectors. But in contrast with the U.S., the private automobile sector joined the ethanol innovation process since the first years of the program.

Supported by government incentives, Brazil was the only country to develop commercially a program with vehicles capable of running on 100% ethanol during the 1980s (J. Goldemberg, 2009). Despite strong incentives and opportunities during the 1970s and 1980s, shortage of ethanol and low international oil prices put the program almost to a halt during the 1990s. It was only in 2003 that the flex fuel engine technology allowed consumers to regain trust in ethanol, making the case for strong investments in research and production, thus higher participation in the market. The case of Brazil reveals an innovation trajectory of a technology that took more than three decades to build a self-reinforcing system able to compete with gasoline. Contrary to the U.S., currently the penetration of ethanol in the Brazilian market is high, accounting for 40% of the gasoline demand, thanks in part to the recent success of flex fuel vehicles that today account for 90% of sales of light duty cars (J. Goldemberg, 2009; Jose Goldemberg & Guardabassi, 2009).

1.4 Innovation of low carbon technologies: "carbon lock-in" and functions of innovation

This research uses theories that draw on the systems of innovation school, which treats innovation as a system composed of agents, networks, and institutions that interact to produce, and diffuse new technologies. The systemic view of innovation goes beyond the linear model of “technology push” and “market pull”, emphasizing the critical role of interaction, collaboration, and reciprocity among firms, suppliers, customers, and other agents participating in the innovation process. The innovation systems approach considers learning a fundamental mechanism to promote technological change. Learning stimulates the generation of new knowledge or new combinations of existing knowledge within the system. The innovation process is evolutionary and cumulative; it is influenced by political, economic, institutional, and social factors, and has feedback mechanisms (Edquist, 2005). Innovation systems can take different dimensions, and have been studied at the national (B. A. Lundvall, 1992; B.A. Lundvall, 2007; Nelson, 1993), at the sectoral (Malerba, 2002), at the regional (Saxenian, 1994), and at the technological level (Carlsson, Jacobsson, Holmen, & Rickne, 2002b; Carlsson & Stankiewicz, 1991).

In order to understand the socio-institutional environment that surrounds the emergence of ethanol over time, this study analyzes ethanol evolving within a technological innovation system (TIS). Technological innovation systems refer to the set of institutions, agents, and networks that use resources available to produce technological change (Carlsson & Stankiewicz, 1991). Using innovation systems at the technology level and not at the national, sectoral, or regional level facilitates the task of understanding the dynamics of innovation over a long period of time, because it reduces the scope of the analysis to agents, networks and institutions specific to the technology in question. It facilitates the close examination of whether the components of TIS are supporting the emerging technology and whether the technology is reinforcing the agents, institutions, and networks around it (Marko P. Hekkert & Negro, 2009). Technological innovation systems have been useful to explain the process of innovation of emerging technologies (B. A. Lundvall, 2007).

The concept of technological change is critical to understand the context within which low carbon technologies emerge. Technological change is an evolutionary process that results from a combination of new technological capabilities or from new institutional or organizational arrangements of old technological competences (Carlsson et al., 2002; Carlsson & Stankiewicz, 2002). Technological change is endogenous to innovation systems, that is, it is determined by technological, economic, political, and social factors embedded in the technology's innovation environment. Technology change is path dependent, that is, without external events it tends to follow a specific path, or a technological trajectory consistent with established knowledge and procedures to solve specific problems - a "technological paradigm" (Dosi, 1982). Technological change happens as a result of interactions among economic, social, and institutional factors once a technological paradigm has been established; thus, the phenomenon of "path dependency" (David, 2000). In this context, past events related to a technology become relevant and have important implications for the understanding of the innovation process. Over time, stronger linkages between technology and its institutional and regulatory environment, along with less uncertainty about technology developments, create conditions for self-reinforcing mechanisms, or increasing returns to adoption (T. Foxon & Pearson, 2008). In the absence of external forces, increasing returns to adoption lead to "lock-ins" of incumbent technologies, creating barriers against potential rivals (David, 2000; Timothy Foxon, Kohler, & Neuhoff, 2008; T. Foxon & Pearson, 2008).

A successful innovation outcome of low carbon technologies can be determined by the technology's ability to displace the incumbent fossil fuel, and penetrate in the market. Moreover, a successful innovation process is one that takes the emerging technology to a self-reinforcing path of positive feedbacks and market penetration. In the case of ethanol, a successful innovation process is one that displaces gasoline and creates conditions for a self-sustained growth in the transportation market. The innovation system surrounding ethanol may contribute or hamper its successful innovation trajectory.

The innovation of ethanol is one facing “lock-in”, because ethanol needs to compete and survive within a system where actors, networks, and institutions still remain “locked in” to fossil fuel technologies, in the case, gasoline and oil. Because of the public good nature of energy security and climate change mitigation, market forces cannot drive innovation without public policy interventions. (Timothy Foxon et al., 2008b). The institutional and socio-economic environment reinforces the market consolidation of fossil fuels, thus making more difficult the process of innovation of ethanol. The reality facing the ethanol industry in the United States illustrates some of the barriers typical of the innovation process of “low carbon” technologies. To compete with long time established carbon-based (derived from fossil fuels) technologies like gasoline, ethanol needs to break the inertia of a system that is designed to run on fossil fuel-based technologies. This phenomenon, known as “carbon lock-in” (Brown, Chandler, Lapsa, & Sovacool, 2007; G. C. Unruh, 2000; Gregory C. Unruh, 2002; Gregory C. Unruh & Carrillo-Hermosilla, 2006), has been a barrier in the process of innovation of low carbon technologies. For example, gasoline prices and tax burden in the U.S. are low compared to other countries[6] , making more difficult the competition of ethanol with gasoline in the U.S.; the fuel distribution system (transportation from industrial plants in pipelines) is expensive and it has been conceived to transport fossil fuels (sunk costs); only a minority of gas stations is equipped with ethanol pumps. Most light duty vehicles sold have gasoline only engines that take up to 10% ethanol; flex fuel vehicles (FFVs) are minority and most run on gasoline because of lack of distribution infrastructure; automakers don’t invest in flex fuel vehicles because there is no infrastructure, and gas stations don’t invest in ethanol pumps because there are not enough FFVs. Breaking the barrier of “carbon

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[6] As of November of 2008, average retail prices of gasoline in the US was US$ 2.12/gal, against 4.77 in Brazil, 3.60 in Chile, 2.95 in Argentina, 2.80 in Mexico, 5.75 in France, 5.45 in UK, and 5.90 in Germany in the same period (GTZ 2009 at http://www.gtz.de/en/themen/30005.htm).

lock-in" and displacing the incumbent technology is then a complex process, it warrants government programs, and takes a long time to happen. Moreover, because of the public good nature of climate change and energy security, the process of innovation of ethanol faces market failures. For this reason, public policies to stimulate innovation of ethanol are justified to guarantee the optimal provision of those public goods to society (Popp, Newell, & Jaffe, 2009; Stern, 2007).

1.5 Functions of innovation systems

Scholars have been studying the innovation process by monitoring the functions or activities of innovation around a technology. They argue that the innovation process is long, complex, and dynamic. A technological innovation system performs well when technological possibilities overcome barriers in the system and generate consumer products in the market (Carlsson et al., 2002).

Innovation relates to the development, diffusion, and adoption of technology. Because most low carbon technologies have to compete with fossil fuels that dominate the market, in this case the performance of innovation may be explained by a measure of how the clean technology breaks "carbon lock-in", and displaces the incumbent (fossil) technology in the market. This process of innovation is intrinsically dynamic, complex, and evolutionary. To facilitate understanding of the dynamics of the innovation process of low carbon technologies, some scholars developed a methodology to monitor and measure the functions or activities of innovation systems over time. They claimed that the successful performance of innovation systems depends on the intensity of each function and relies on the level of interaction among its functions over time, that is, how functions interact with each other to form positive (virtuous) or negative (vicious) cycles of innovative activity (Anna Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; M. P. Hekkert, Harmsen, & de Jong, 2007; Marko P. Hekkert & Negro, 2009; M. P. Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007; Negro, 2007). Scholars suggest that a number of functions need to be present and fulfilled : 1) entrepreneurial activity to emerge and displace the incumbent technology; 2) knowledge creation to stimulate learning by experimentation; 3) knowledge diffusion to stimulate learning by interaction; 4) guidance of research to guide strategic decision making and stimulate positive expectations around the new technology; 5) market formation to create a niche market and stimulate the penetration of the new technology; 6) investments in material and human resources; and 7) legitimation of the new technology to help break the inertia of the incumbent technology within the institutional and socio-economic environment (Anna Bergek et al., 2008; Marko P. Hekkert & Negro, 2009; M. P. Hekkert, Suurs et al., 2007).

The functional analysis of innovation is a conceptual framework in formation. Different works suggest different lists of functions of innovation. Bergek et al. (2008) provides a complete account of different versions, and concludes that over time most authors have converged around a common set of functions. Some empirical research has confirmed that the seven functions that have been described previously are relevant for the study of the process of innovation of some low carbon technologies (Marko P. Hekkert & Negro, 2009). But previous research does not confirm whether the set of functions explains the overall dynamics of the innovation process. In other words, it is possible to affirm that the proposed functions of innovation are necessary to explain dynamics of innovation of low carbon technologies, but the literature has not empirically tested whether the set of functions is sufficient to explain the dynamics of innovation of low carbon technologies.

Bergek and colleagues (2004, 2008) propose an additional function of innovation named “Development of external economies”. The authors claim that at the onset of the innovation process, an emerging TIS enlarges its scope of innovation by building a number of linkages with new actors who become active within the TIS. This dynamic creates opportunities for the TIS to generate positive externalities within the process of innovation, such as pooled labor work, a larger and high quality supply of intermediate goods, and increased flow of knowledge within the system (Anna Bergek et al., 2008; A. Bergek, Jacobsson, & Sandén, 2008; Jacobsson, 2008; Jacobsson & Bergek, 2004). The function "Development of external economies" has not been tested empirically by studies mapping the innovation of emerging technologies (Anna Bergek et al., 2008).

<u>The downstream market may contribute to the process of innovation</u>

This dissertation contributes to the field by building on the function "Development of external economies", and proposes a function that is specific to the downstream market. Downstream market relates to users of the technology or product carrying the technology. In the case of ethanol, the downstream market relates to car producers, and also to fuel distributors. As it is defined in this study, the downstream market applies to products and technologies that are not at the end of the supply chain. In other words, downstream market relates to industries or sectors of the economy, and not to final consumers.

When it develops capabilities to support the upstream market, or the producers of the emerging technology, a downstream market that has goals and strategies aligned with players of the upstream market co-evolves, converges, and ultimately "embraces" the technological innovation system. At some point, it participates and becomes an integral component of the innovation process. This study proposes the function "Building of capabilities in the downstream market" as an additional function to the set of the seven functions previously proposed. This function can be considered a sub-set of the function suggested by Bergek and colleagues, because the downstream market is a sub-set of the economy external to the technological innovation system (TIS).

By developing a capability (technological, industrial, commercial, institutional), the downstream market becomes increasingly embedded within the TIS, developing a niche market for the new technology to emerge. This concept is consistent with Carlsson et al.(2002), who argue that innovation systems perform well when technology possibilities fulfill market demands, and when technologies can match market competencies (Carlsson & Stankiewicz, 2002), leading towards an alignment of goals between producers and users of technology. The potential contribution of the downstream market is greater when the technology is emerging and needs to face barriers of the incumbent technology. In the early life of a technology or a product, there are few players within the technological innovation system. This stage of the innovation process creates opportunities for building linkages between technology producers and technology users that can be critical for the future innovation trajectory of the new technology. In this context, the downstream market can take the lead in advancing its own products and technologies to maximize the advantages of the technology produced by the upstream market, therefore maximizing the chances that the emerging technology will displace the incumbent in the short term. The usefulness of building capabilities in the downstream market is less evident in non emerging technologies and, as has been mentioned, in consumer products.

The renewable energy sector can benefit from a downstream market more akin to clean energy. As has been mentioned previously, low carbon technologies cannot always take advantage of the low cost infrastructure available to fossil fuel-based energy systems. In this sense, low carbon technologies face an additional barrier to displace fossil fuel technologies. Facilitating the connection and maximizing potential synergies between the downstream and upstream markets can mitigate the intrinsic barriers between the production and use of renewable energy systems. For example, building of capabilities in the downstream market can be applied to home systems. The innovation and institutional environment that regulates energy use in home systems can induce the use of clean technologies such as photovoltaic (PV) solar panels and heating pumps by engaging the home building sector (civil engineering and architecture) to build capability in sustainable systems in coordination with target technologies such as PV panels. The same concept can be applied between intermittent sources of energy such as wind and the development in smart grid systems that develop an expertise in predicting energy generation following climate models. The main goal is to engage the downstream market and to maximize coordination between producers and users of clean technologies.

Very often, different technological innovation systems compete for the same downstream market. This is the case of the TIS ethanol and TIS gasoline competing for the automobile sector (combustion engines). By developing a specific capability, the downstream industry can attract the emerging technology to the detriment of the incumbent. In the case of ethanol, the automobile sector (including fuel distribution) has an active role in developing a niche that facilitates the use of ethanol by the final consumer. The more the automobile sector fulfils this role or function, the better for the performance of the ethanol TIS. This function, however, does not operate in isolation. It is part of a set of functions that interact to form positive feedback mechanisms to create long term innovation. For example, the development and commercialization of vehicles having engines with flex-fuel technology can facilitate the penetration of ethanol in the automobile market. The convergence between the ethanol and the downstream market (fuel distribution and automotive sectors) is critical to stimulate the penetration of ethanol and the displacement of gasoline in the transportation sector, or it is critical for the performance of innovation of ethanol over time (fig.2).

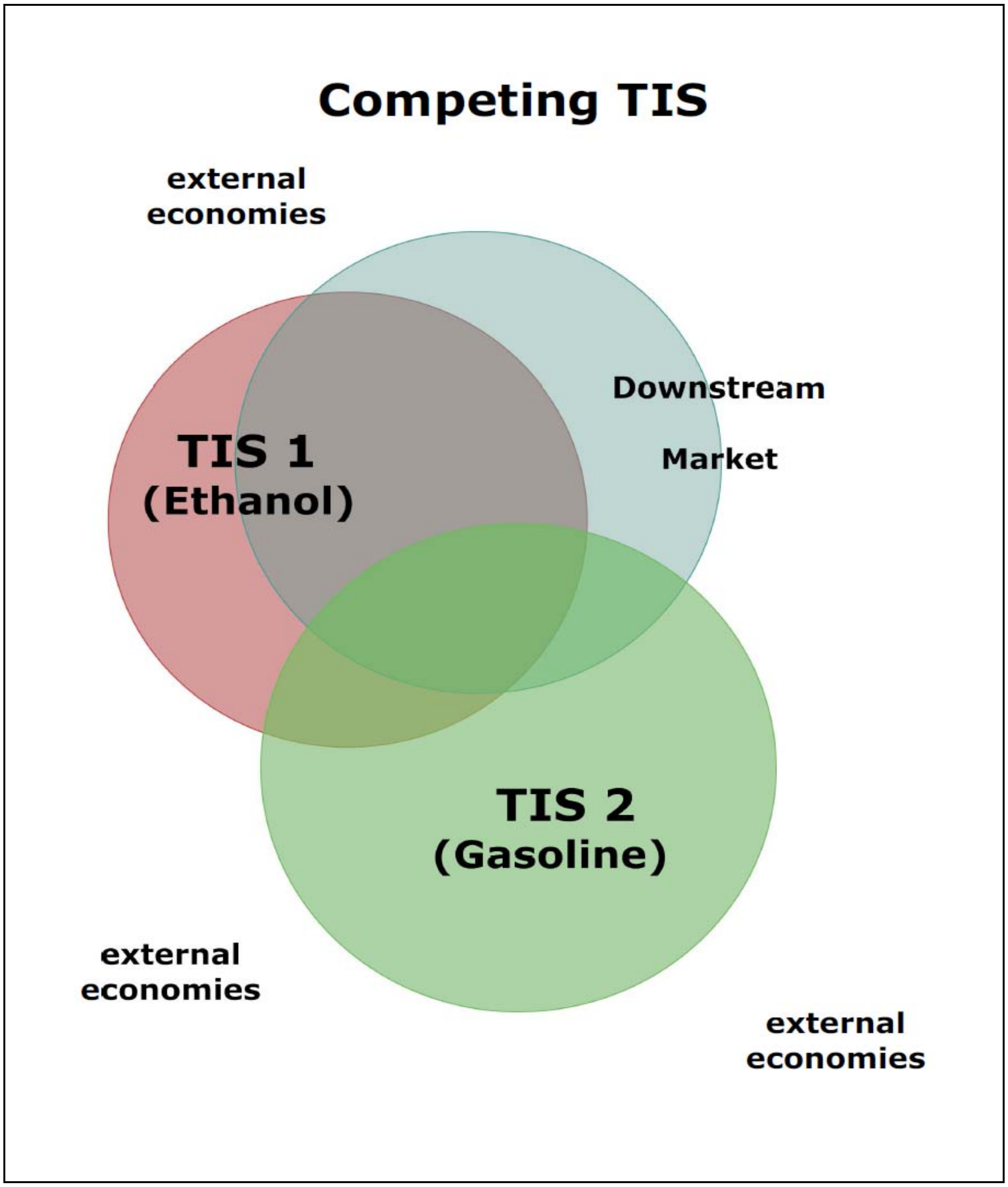

**Figure 2: TIS 1 (ethanol) competing with TIS 2 (gasoline)
for the Downstream Market (automobiles - internal combustion)
Source: Own author**

The performance of the TIS composed of eight functions of innovation is assessed quantitatively by measuring the number and the intensity of functions of innovation over time. It is assessed qualitatively by identifying interactions among functions that induce or block the process of sustained innovation. Because functions interact and reinforce each other, all functions need to be present and active. When all functions are individually fulfilled and interact with each other, a TIS can successfully nurture a sustained process of innovation (development, diffusion, and adoption of new technologies).

Using the functions of innovation to map the innovation process of ethanol in the U.S. and in Brazil between 1975 and 2008, this study raises the following questions:

1.Q What are the differences between the functions of innovation of ethanol in the U.S. and Brazil? How have those differences evolved over time?

2.Q Which are the strongest and weakest functions in each country? How do they compare to each other?

3.Q What are the causal patterns (blocking and inducing mechanisms) that explain the outcomes of ethanol development for each country over time?

The literature leads us to expect that the function Guidance of Research (F4) is an important trigger of innovation within the ethanol system. The renewable energy sector requires particular conditions for innovation to happen. In order to overcome "carbon lock-in" and penetrate in the fossil fuels market, the system demands incentives that generate a positive expectation for technology producers (supply side), and for technology users (demand side). The extent to which carbon intensive technologies are embedded in the technological, economic, and institutional environment will dictate how much incentive renewable technologies will need to penetrate in the market. Some may include regulations, procurement, market obligations, pricing, training, R&D investments, among others. In this sense, the expectation around the technology plays a critical role driving decisions around investments in R&D, production, and over the legitimation of the technology among the actors of the ethanol TIS. I expect Guidance of research (F4) will have a positive effect in knowledge creation and knowledge diffusion (F2), (F3) of ethanol, promoting more investments in resources (F6), boosting entrepreneurial activity (F1). This pattern has been identified by authors exploring cases on biomass digestion and biomass co-firing in Germany (Marko P. Hekkert & Negro, 2009; Negro & Hekkert, 2008); biomass gasification and biomass digestion in the Netherlands (Marko P. Hekkert & Negro, 2009); biofuels in Sweden and in the Netherlands (Hillman, Suurs, Hekkert, & SandÃ©n, 2008; Suurs & Hekkert, 2009); and biopower (CHP) in Sweden (Jacobsson, 2008). These cases indicate that there is a cumulative pattern where the function Guidance of Research is a precursor of a positive cycle of innovation. However, neither of the empirical studies have statistical power, nor sufficient qualitative insights to generate persuasive and testable hypotheses. Since the ‘functions of innovation’ is a concept in formation, most empirical studies concentrate in testing the usefulness of the list of functions. They also focus on providing qualitative insights that enrich our understanding about the process of innovation of low carbon technologies. By answering the research questions, this dissertation will contribute to the task of validating the usefulness of the set of functions of innovations proposed by the literature.

1.6 Policy relevance: biofuels innovation is a priority in President Obama’s agenda

The study of innovation of biofuels is relevant in this moment when the Obama administration is proposing steps to boost the production of sustainable biofuels[7] . This study shows that despite government policy and action towards the development of biofuels in the U.S., the industry has not been able to unlock “carbon lock-in” and displace gasoline in the market in a sustained way. This analysis contributes to the decision making process by clarifying the process of innovation of biofuels. The

[7] http://www.whitehouse.gov/the-press-office/obama-announces-steps-boost-biofuels-clean-coal.

analytical tools used in the study suggest that biofuels occupy a broad innovation environment, one that requires a policy coordination and strategic convergence between agriculture, industry, and the transportation sector.

This research goes beyond an assessment of technological differences. By mapping the functions of innovation over time, it informs how the functions interact to induce or block the process of innovation growth. At the methodological level, the research offers the possibility to analyze and compare biofuel ethanol as a technological innovation system between an industrialized and a developing country over time. It also offers American policy makers a benchmark analysis of three decades of development of biofuel ethanol that culminated in a successful program of alternative fuels in Brazil[8] (J. Goldemberg, 2007; OECD, 2008; Sandalow, 2006).

1.7 Methodology: Process theory, and historical events as unit of analysis

The functions of innovation perspective is a causal and evolutionary framework that cannot be tested by an independent/dependent variable relationship, but rather by a mechanism of path-dependency, with multiple causes and outcomes, or a sequence of causal relationships with self-reinforcing characteristics (Gerring, 2001, 2007). Therefore, explanations of outcomes are based on patterns of temporal and geographical variation of functions of innovation, such as positive (virtuous cycles) and negative (vicious) feedback (Pierson, 2003). By plotting the evolution of functions over time, I expect to identify the patterns of development for each function, and the emergence of

[8] Brazil has the most competitive ethanol process in the world. 90% of Brazilian light duty vehicles can run on gasoline, ethanol or any mixture of the two fuels.

positive and negative feedback, providing support for a comparative analysis between the U.S. and Brazil.

The methodology is based on process theory, which claims that the process of innovation relates to the chain of events that represent how people interact to develop and implement new concepts and ideas over time. The events are assumed to represent instances when change is observed within the innovation system. In this research, change relates to the longitudinal change in the functions of innovation systems of ethanol, or in the context influencing change over time. The research design assumes that each newspaper article represents an empirical observation of an event, also the object of analysis for the purpose of research.

The data consists of newspaper articles from the U.S. and Brazil containing news or describing events related to ethanol in the two countries between 1975 and 2008. The methodology, described in detail in chapter 4, follows 6 steps:

1. Bibliographic research: search in the international database Lexis Nexis Academic[9] , limiting to U.S. newspapers New York Times and Washington Post. The search was complemented with archival research at the Brazilian newspaper O Estado de Sao Paulo. The search generated a dataset of 1750 articles organized as a list of chronological events that were individually imported to NVivo, a software specialized in qualitative analysis.

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[9] Database containing searchable data of legal, news, and business sources worldwide.

2. Coding of events: using NVivo capabilities, each event was coded into categories (functions of innovation) defined by the theory, following a codebook previously designed through an inductive coding process[10] .

3. Data analysis and plotting: once reported events (represented by newspaper articles) were classified according to the codebook, they were plotted against time to analyze quantitatively the evolution of each function of innovation for each country over time.

4. Interviews with specialists: This step gathered information obtained from unstructured interviews with specialists from the U.S. and from Brazil. The goal of the interviews was to complement the data from newspapers and gray literature with insights from specialists who have experienced many years of the innovation process of ethanol. Because each specialist has a different focus, the interview was geared towards the experience of each interviewee.

5. Process analysis: a narrative story line was developed by using a chronological sequence of events. This step took into account the different contexts of each country, and the exogenous factors influencing the functions and the development of innovation over time. The goal of this step was to explain how functions interact with each other leading to positive and to negative feedback mechanisms. By linking narrative to graphic representation of functions, the goal of this step was to identify the causal patterns leading to the emergence of positive or negative cycles of change and development. Gray literature and interviews with specialists were used to complement and validate the inputs obtained from newspaper articles.

[10] I create a sub-level of coding subordinated to the main functions of innovation. I do that for all events or articles published by the New York Times. This process helped me create a codebook with detailed descriptions for each function of innovation.

6. Comparative analysis: the steps described were applied to the two countries, providing the necessary data to compare the patterns of development of innovation in ethanol over time.

The remaining of the dissertation includes the following chapters:

Chapter 2 explores the theories of innovation. It starts by introducing the concept of innovation systems, and how the concept evolved from the classical theories of innovation. The chapter defines technological change, and introduces the concepts of path dependence, and increasing returns to adoption as the source of technological lock-ins. In the case of low carbon technologies, carbon lock-in has been a significant barrier against the innovation of clean technologies like ethanol. The innovation system school now has a scholarship of its own, with programs and studies dedicated to exploring the concept in its different dimensions: at the national, at the sectoral, at the regional, and at the technological level. Technological innovation systems relate to the set of actors, networks, and institutions that interact to produce innovation. The application of the functions of innovation using technology as the unit of analysis has been explored more recently by scholars investigating the emergence of low carbon technologies. The chapter reviews the literature on the functions of innovation systems, providing more detail on previous work developed on the field of biofuels.

Chapter 3 presents a general description of the ethanol technology in the U.S., and the technology in Brazil. The chapter explores the different dimensions of learning, and shows the impact of learning in measures of agricultural and industrial productivity, energy consumption, and carbon emissions for corn ethanol in the U.S. and sugarcane ethanol in Brazil. It is argued that time and learning is essential for innovation to happen. The case of corn ethanol illustrates the impact of different technologies (use of different energy sources) on the environmental impact of corn ethanol production. The chapter shows that the use of low carbon technologies can improve the environmental impact of corn ethanol. In fact, there is a significant gap in energy consumption between a plant powered by coal and a plant powered by biomass. The chapter claims that government policies may stimulate the supply and demand of more sustainable corn ethanol in the U.S. Brazil has adopted the use of bagasse (fiber residue from sugarcane stalks) to power its industrial plants. This technological and industrial decision has been critical for the positive energy balance, and competitiveness of Brazilian ethanol.

Chapter 4 describes the data, the coding process, and the methodology. The chapter starts by providing the basic assumptions for the operationalization of variables. It then describes process theory, because it is the theoretical source from which the methodology is developed. In process research, the goal is to create a chronological list of events around a specific technology, code the events in categories defined by the theory, and identify the processes or the patterns that explain how innovation occurs. The chapter describes the procedure that is applied to two case studies of the evolution of ethanol during the last thirty years, in the U.S. and in Brazil.

Chapter 5 answers in part the second research question, identifying quantitatively the strongest and weakest functions in each country. It also compares the evolution of events for the U.S. and Brazil over time, showing that the period after 2000 is the strongest in innovation activity for the two countries. Chapters 6 and 7 bring the results drawn from the qualitative analysis. Chapter 6 develops the process analysis or the narrative for the U.S., supported by data and graphs (quantitative analysis). Chapter 7 presents the same as chapter 6, but for Brazil. Chapter 8 compares the two countries and Chapter 9 concludes with discussions and policy recommendations.

CHAPTER 2
INNOVATION AS A SYSTEM

This chapter reviews the literature of innovation systems, focusing on variations using technology as unit of analysis. The chapter presents the structural dimensions of technological innovation systems (TIS), and explores in more detail the functions or tasks of technological innovation systems in the context of innovation of low carbon technologies.

Scholars have been developing the field of innovation studies for many decades, exploring the intersection between science, technology, and economic growth (Stephan, 1996). By opening the “black box” (Rosenberg, 1982) of technological change, and by endogenizing technology into the process of innovation (Nelson & Winter, 1982), institutional and evolutionary economics challenged the basic premises of neoclassic economics. The analysis of how institutions shape the evolutionary process by which technological progress takes place became the theoretical source of scholars who later developed the concept of innovation systems (Freeman, 1987; B. A. Lundvall, 1992; Nelson, 1993). Under the systemic approach of innovation, research and development is necessary but not sufficient to transform knowledge into economic growth. A preliminary comparative bibliographic analysis between the U.S. and Brazil confirms this premise. Assessment of the scientific literature indexed by ISI Web of Science during the last 30 years, shows that U.S. institutions have published almost four times as much as Brazilian institutions in the field of biofuels. And yet, as this research project will show, the industry in Brazil performs better in cost competitiveness, energy and land intensity than its counterpart in the U.S.

Lundvall (1992) underlined the importance of interaction between producers and users of technology, and the role of institutions to bridge technology capacity to market needs. By acknowledging that actors make decisions under conditions of "bounded rationality" (Simon, 1997), the innovation systems concept underlines the critical role of individual and organizational interaction, defining patterns of behavior that can ultimately predict how the process of individual and group learning takes place (Nelson, 2002). Under the systemic approach, firms are assumed not to operate in isolation, and external linkages become critical determinants of innovation. Challenging the neoclassic approach, investments in technology take place even under uncertainty.

According to the innovation systems framework, knowledge is localized. Firms learn from different sources, and in order to survive competition, they adapt their routines to the environment that surrounds them. Inherent to the evolutionary tradition is the concept of path dependency that characterizes the process of technological change as "learning by doing" (Arrow, 1962), "learning by using" (Rosenberg, 1982), and "learning by interacting" (B. A. Lundvall, 1992; 2002). Scholars developing the innovation system approach assume increasing returns to adoption and learning, thus rejecting the linear nature of technological change. Therefore, time and history are relevant, since the performance of a new technology depends on past decisions embedded in technologies and institutions from the past (T. J. Foxon et al., 2005).

The systemic approach of innovation was first introduced by Freeman (1987), who developed the concept of National Systems of Innovation to study Japan's industry during the 1980s. Nelson (1993) further developed the concept to compare how different national economies evolve over time. Edquist (1997) provides a general definition of national systems of innovation as "all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovations" (Edquist, 2005).

The systemic approach proved to be useful to explain innovation in regions (Cooke, 2001; Saxenian, 1994), sectors (Malerba, 2002), and around specific technologies (Carlsson & Stankiewicz, 1991). Aware of its limitations in the study of developing countries, and in explaining and assessing the dynamics of innovative activity overtime, Lundvall (2007; 2002) more recently has broadened the framework to incorporate the concepts of social capital, and capacity building.

In order to characterize the evolution of ethanol, this dissertation uses the technological innovation systems (TIS) approach, a concept developed by Carlsson and Stankievicz in 1991 that later converged into the field of study of innovation systems. TIS are innovation systems performing around a specific technology, or a product. Taking a technology or a product as the boundary of a system facilitates the task of understanding the temporal and geographical evolution of innovative activity. In the case of emerging technological systems, actors and institutions interact to combine capabilities that create innovation. By displacing the incumbent technology, the new technology becomes entrenched in the new socio-economic environment (Carlsson & Stankiewicz, 1991; Jacobsson & Johnson, 2000). Bo Carlsson and colleagues have been working on the Technological Innovation System approach since 1987, within the scope of a major project commissioned by the Swedish National Board for Industrial and Technical Development (VINNOVA). This dissertation draws on more recent version of the theory, when the authors broadened the framework to analyze the set of technologies in the field of biotechnology.

Carlsson et al. (1991) argue that TIS are inherently dynamic, and that identifying relationships and feedback loops among the system components overtime are the main goals of using TIS as an analytical tool. Technologies[11] are embedded in networks of institutions and actors, which in turn use the resources available to produce innovation. Thus, in order to evaluate the performance of a technological innovation system, it is critical to understand the relationship between the technology and the innovation system

[11] Here technology embodies products, machines, processes, and softwares, as well as the technical knowledge incorporated on them (Bergek et al. 2008).

that surrounds it. Very often TIS overlap with parts of different sectoral and national innovation systems, and sometimes the boundaries of a technology coincide with national, international, or regional borders (M. P. Hekkert, Suurs et al., 2007; Negro, 2007).

Scholars have used the TIS approach to explain and compare the development of different technologies over time. The concept has been used to analyze the economic performance of factory automation in Sweden (Carlsson, 1995), to compare biotechnology clusters between the U.S. and Sweden (Carlsson & Braunerhjelm, 2002), and to assess the evolution of a number of emerging technologies in the energy sector (Carlsson, Elg, & Jacobson, 2006)[12] . Many studies revealed that technological innovation systems can be analyzed at the structural (Carlsson et al. 2002) and at the functional level (M. P. Hekkert, Suurs et al., 2007; Jacobsson & Bergek, 2004).

2.1 Technological Innovation Systems – technological, institutional, and economic dimensions

In a more recent version of the concept, Carlsson et al. (2002) argue that taking into account the different structural dimensions of the system facilitates understanding innovation dynamics over time and across different regions. The authors define TIS as a set of "knowledge and competence networks" which, stimulated by innovative activity, can be transformed into "development blocs", or "synergistic clusters of firms and technologies within an industry or a group of industries" (Carlsson et al. 2002: 10). They propose three structural dimensions for analysis:

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[12] See Carlsson (2006) for a review of development and use of the Technological Innovation Systems approach.

- Technological or cognitive dimension: defined as “design spaces formed by clusters of complementary technical capabilities”, where technological growth takes place through the combination of new and old capabilities and applications. These new combinations can result in new technological possibilities.
- Institutional and organizational dimension: represented by the network of actors that form and transform the design space, and which are influenced by policies and institutions that regulate how the techno-economic environment evolves.
- Economic dimension: also called “competence blocs”, which represent “the set of actors who convert technological possibilities into business opportunities and exploit them in economic activity”. One design space can deliver technologies to several competence blocs.

Carlsson et al. (2002) argue that successful technological innovation systems are brought up by the evolutionary dynamics between the technological, institutional, and economic dimensions of TIS. “The confrontation between technological possibilities and the market takes place in an environment largely determined by the actors, networks, and institutions within the system” (Carlsson et al. 2002). Performance of innovation depends on how design spaces (technological dimension) and competence blocs (economic dimension) are able to integrate and address tensions within the innovation systems dynamics. This concept is critical in the realm of low carbon technologies.

2.2 TIS – a functional analytical approach

Scholars studying the field of innovation have developed the concept of functions[13] of technological innovation systems, suggesting a list of functions that innovation systems should perform in order to create, deploy and diffuse new technologies. Scholars have applied the functions of innovation to map innovation of low carbon technologies in biomass digestion and biomass co-firing in Germany (Marko P. Hekkert & Negro, 2009; Negro & Hekkert, 2008); biomass gasification and biomass digestion in the Netherlands (Marko P. Hekkert & Negro, 2009); cogeneration in the Netherlands (M. P. Hekkert, Harmsen et al., 2007), biofuels in Sweden and in the Netherlands (Hillman et al., 2008; Suurs & Hekkert, 2009); and biopower (CHP) in Sweden (Jacobsson, 2008).

The functionalist approach was developed through a collaboration between a group of scholars and policy practitioners from the Swedish Agency for Innovation Systems (VINNOVA), the Chalmers University in Sweden, and the Utrecht University in the Netherlands (Anna Bergek et al., 2008). These scholars and policy analysts searched for theoretical and analytical tools that could complement more conventional approaches they considered more limited to explain the dynamics of innovations systems over time. They proposed to map a longitudinal series of events, and argued that using the functions or activities of innovation systems (instead of or in addition to using more structural indicators) 1) help the analyst capture dynamic trends that very often cannot be revealed by structural factors or variables; 2) help explain the underlying factors shaping innovation system growth; 3) help to identify the blocking mechanisms, failures, or weaknesses hindering or preventing innovation system development; 4) and help the

[13] The concept of functions of innovation is not related to the "functionalist" approach from the social sciences, but instead comes from the field of engineering where systems are designed to perform certain tasks or functions (Negro 2007).

analyst identify the inducing mechanisms promoting development, diffusion, and adoption of new technologies (Anna Bergek et al., 2008; Carlsson et al., 2006). These analytical contributions have had a significant impact for understanding the innovation process of low carbon technologies. The innovation of clean technologies faces barriers or failures, and it deserves government support because of the public good nature of knowledge creation for mitigation of climate change, and energy security. Some factors justify policy intervention in the innovation process of low carbon technologies:

1. "Carbon lock-in" - low carbon technologies face an institutional and socio-economic environment that tends to reinforce the market consolidation of fossil fuels (G. C. Unruh, 2000). For example, because the infrastructure is adapted to fossil fuels, new investments in low carbon technology need to take into account sunk costs of investments in carbon intensive technologies. Also, most institutions are designed to support and benefit fossil fuels.
2. Climate change – according to Sir Stern, climate change is considered a negative externality in economic terms (Stern, 2007). Therefore, social gains from climate change mitigation are greater than private gains, justifying government support to provide the optimal amount of mitigation benefits to society (Timothy Foxon et al., 2008; T. Foxon & Pearson, 2008). This has been the rational for environmental and energy policies.
3. Science & technology – knowledge is a public good, which without public support tends to be undersupplied to society. Therefore, the creation of knowledge for low carbon technologies deserves incentives (such as R&D funding and intellectual property rights) to promote public and private research
4. Energy security – if low carbon technologies are produced and supplied from reliable places and from sustainable sources, then they contribute towards energy security. Policies should promote local entrepreneurship to guarantee energy supply and the development of a vibrant energy industry.

A number of authors claim that mapping the functions of TIS is a useful analytical tool to identify blocking (market failures) mechanisms and suggest inducing mechanisms (policy prescriptions) influencing the performance of innovation systems over time (Hillman et al., 2008; Jacobsson, 2008; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000; Negro & Hekkert, 2008; Negro, Hekkert, & Smits, 2007). The functional perspective has been proved useful in longitudinal analysis of different institutional environments, offering a powerful tool to map the determinants of innovation within the field of renewable energy. Hekkert et al. 2007[14] propose seven functions that explain how innovative activity takes place over time:

- F1: Entrepreneurial activities – entrepreneurs are central to innovation, linking knowledge to market opportunities. Entrepreneurship involves risk and "learning by experimentation".
- F2: Knowledge creation – this function relates to R&D activities, and is directly related to "learning by searching" and "learning by doing". Learning is considered the fundamental aspect of the process of innovation. The functionalist approach leaves the knowledge creation activity open to more explicit ways of acquiring knowledge – through research (learning by searching) – or to less explicit and more implicit ways of learning that takes place through experience (learning by doing) and through social interaction (learning by interacting). Some authors merge knowledge creation and knowledge diffusion within the same function of innovation (Anna Bergek et al., 2008).
- F3: Knowledge diffusion – this function takes place through network of actors who are constantly exchanging knowledge. It incorporates the concept of "learning by interacting" and "learning by using".

[14] The development of functions is the result of a meta-analysis of the innovation systems literature, a collaborative work between research groups from Utrecht University (Innovation Studies), VINNOVA (Swedish Innovation Agency), and Chalmers University.

- F4: Guidance of research – this function relates to events that influence the definition of policy targets, and the establishment of a research agenda that selects the best technology among the options available. Therefore, it affects perception and general expectation in relation to the technology.
- F5: Market formation – it relates to the temporary creation of niche markets, allowing the new technology to thrive in the new environment. In the case of low carbon technologies, the concept of market formation assumes that government intervention is justified to address “carbon lock-in”, climate change, and energy security.
- F6: Resource mobilization – it relates to both, financial and human resources allocated to the technology or product over time. In the case of low carbon technologies, public investments are justified on the grounds of “carbon lock-in”, climate change, and energy security.
- F7: Creation of legitimacy – this function has the goal to counteract the inertia intrinsic of most systems, where there is often a resistance to change. It can be fulfilled by advocacy coalitions or commercial associations that lobby for the new technology. Very often, politicians and public authorities act to support the agenda of a specific technology. Within a context of “carbon lock-in”, low carbon technologies have a deficit of legitimacy among investors, policy makers, and the society.

The seven functions of innovation described represent processes happening simultaneously within a technological innovation system. From a theoretical perspective, they are consistent with the process of innovation as described by Lundvall (2007), who argues that innovation is about learning processes, where knowledge is the most important resource (B. A. Lundvall, 2007). The first three functions of innovation describe the different learning processes. F1-Entrepreneurial activity is about learning by experimenting; F2-Knowledge creation is about learning by searching and learning by doing; and F3-knowledge diffusion is about learning by using and learning by interacting. The four additional functions relate to the barriers or failures specific to the process of innovation of low carbon technologies: F4-Guidance of research relates to the “risky” nature of innovation of low carbon technologies - carbon lock-in. Clear policy targets and positive expectations about the technology facilitate decisions that support innovation in clean technologies; F5-Market formation relate to public policies that address market barriers, and they are justified on the grounds of carbon lock-in, and climate change; F6-Resource allocation map investments in R&D, demonstration, and manufacturing. Additional government support may be justified on the grounds of carbon lock-in, climate change, and energy security; and F7-Legitimation identifies legitimacy issues of low carbon technologies, a weakness explained by carbon lock-in.

The literature on innovation systems presents a number of studies using functions of innovation to assess the performance of innovation processes. Overall, most studies use similar sets of functions at the conceptual level, although naming the functions in different ways (Anna Bergek et al., 2008). Galli and Teubal (1997) differentiate between hard (R&D and supply of scientific and technical services) and soft functions (diffusion of knowledge, implementation of certifications and standards, promotion of science and technology through museums, and professional coordination through professional associations) (Galli & Teubal, 1997). Rickne (2000) suggests functions such as 1) creation of human capital; 2) direction of technology, market, and partner search; 3) market creation, market regulation; 4) networking; 5) legitimation of technology and firms; and 6) financing, creation of labor market, etc. Bergek et al. (2008) proposes seven functions: 1) knowledge creation and diffusion; 2) entrepreneurial experimentation; 3) influence on the direction of research; 4) market formation; 5) development of positive external economies; 6) legitimation; and 7) resource mobilization. See (Anna Bergek et al., 2008) for a thorough discussion and comparison among each one of the studies.

2.3 Functions of innovation and the performance of innovation

So far, it has been argued that the main goal of technological innovation systems is to maximize innovation, that is, the development, diffusion, and adoption of new knowledge, or technologies (Anna Bergek et al., 2008; Carlsson, Jacobsson, Holmen, & Rickne, 2002a). Therefore, the ultimate goal of different technological innovation systems (TIS) is to support and nurture an environment that facilitates the innovation process. Given the growing interdependency between innovation and economic prosperity, policy makers make use of different analytical tools to measure and compare the performance of technological innovation systems across different countries (Carlsson et al., 2002a). To assess TIS performance, one needs to define performance indicators, level of analysis, and the importance of each indicator (since the weight of each indicator may change with the level of maturity of the technology to be analyzed) (Carlsson & Stankiewicz, 2002). Scholars have suggested different indicators: for example, 1) generation of technology can be measured by number of scientific publications, number of patents, investments in R&D, number of scientists, etc.; 2) diffusion of technology can be measured by number of spinoffs, mobility of professionals, number of licenses, joint ventures, etc.; 3) and economic activity can be measured by volume of sales, market share, number of new companies, etc. (Carlsson & Stankiewicz, 2002; Rickne, 2000). Some of these indicators relate to the components of innovation systems, and may not reflect the systemic nature of the environment where emerging technologies evolve (Carlsson et al., 2002b).

As previously argued, to accomplish the final goal of developing, diffusing, and adopting technologies, a TIS performs different tasks, or activities, or functions. The performance of a TIS can be assessed by the intensity (strength) and/or quality (how functions interact) of the tasks/functions fulfilled by the different components of the TIS (Anna Bergek et al., 2008). In this way, the measurement of performance is done at the systemic level, and not at the system's components level. The systemic nature of TIS presupposes actors or network of actors performing tasks that contribute to the innovation process. Measuring tasks or functions instead of indicators at the system's component level moves the analytical focus from actors and institutions to the process of innovation. This additional analytical perspective may add important clues about weaknesses or failures in the innovation process, and about which inducement mechanisms (translated into policy interventions) may accelerate the process of innovation of a particular technology. A TIS performs well if a large number of functions are present and are fulfilled by the components of the system. Moreover, since functions interact, functions can also be fulfilled by the effects of other functions. Therefore, performance is not assessed by a dependent/independent variable relationship, but by a mechanism of path-dependency, with multiple causes and outcomes, or a sequence of causal relationships with self-reinforcing characteristics.

2.4 Functions of innovation and ethanol

While the seven functions of innovation proposed by Hekkert et al. (2007) are broad categories that can be applied to a large pool of technologies, they also reveal to be a useful theoretical approach to study the evolution of biofuels, as demonstrated by Suurs et al. (2007, 2009) and by (Hillman et al., 2008) in the cases of biofuels in the Netherlands and Sweden. Those studies show that the functions of innovation are useful indicators to compare the performance of innovation of biofuels between Sweden and the Netherlands, and to identify the weaknesses and strengths in the innovation process for each country over time.

In Suurs et al. 2009, the authors use the functions of innovation to map the evolution of TIS biofuels in the Netherlands. They assess the performance of two processes for the production of biofuels: the 1st generation technology relies mainly on edible feedstocks and is the one commercially available; the 2nd generation technology is not available at commercial scale, and uses feedstocks that don't compete with the food and feed markets. Separating the analysis by the two groups of technology is important to determine whether programs to promote the 1st generation technology have a positive effect on the development of the 2nd generation technology. They apply "historical event analysis", and use publications covering biofuels from 1990 until 2007 as the empirical representation of events. They classify reports of events according to the designated function of innovation, indicating whether they relate to the 1st, 2nd, or a generic class of biofuels. Results reveal that 1) lack of policy definition (-F4) and the debate about the environmental benefits of biofuels (-F7) in the 1st generation technology prevented the development of 'entrepreneurial activities' (-F1) in the industry, thus limiting the possibilities for the formation of positive cycles of development during the early stages; 2) government programs were geared towards R&D of 2nd generation technology (F2), but did not include a strong emphasis on market development (-F5) of 1st generation technology. Without an established niche market, investors and entrepreneurs did not have enough incentives to invest in a risky and capital intensive 2nd generation technology. In 2003, the European Union Directive on Biofuels implemented a broad innovation policy for biofuels and established incentives for 1st and 2nd generation biofuels, determining that the 1st generation would serve as a bridge to the 2nd generation technology. This change in policy and priorities was implemented at the national level through a tax exemption (F5) towards 1st generation technologies, reassuring major stakeholders (F4), promoting further research, diffusion of knowledge (F2,F3), triggering entrepreneurship (F1), and raising the expectations about the future of biofuels (F4). Therefore, an external event – the European Directive on Biofuels – served as a 'guidance of research' (F4) at the national level, justifying the implementation of policies to help create a market – 'market formation' (F5), increasing positive expectations (F4), increasing 'creation of knowledge' (F2), 'diffusion of knowledge'

(F3), ‘entrepreneurial activity’ (F1), and closing the loop increasing the expectations in relation to biofuels (F4).

In Hillman et al. (2008), the authors use the functions of innovation to compare the performance of biofuels innovation systems between the Netherlands and Sweden. They underline the importance of external events, that is, exogenous factors to the system that influence the trajectory of innovation. Some of these factors include oil supply (oil chocks price volatility), air quality (greater concern in Europe beginning in the 1980s), European agricultural policy, and climate change (signing of Kyoto Treaty by EU members in 1998). The authors recognized the difference between 1st and 2nd generation technologies of biofuels, and the impact of policy in each of the two generations of technology for each country. As has been argued by other authors, despite the debates about the sustainability of 1st generation technologies to produce biofuels, the European Commission supported the more conventional technologies on the grounds that it would serve as a bridge to facilitate access to the 2nd generation technology (Hillman et al., 2008).

The authors used the functions of innovation to explain the different performances of biofuels innovation systems for Sweden and the Netherlands. First, the Swedish innovation system benefited from a stronger function ‘guidance of research’ (F4), as indicated by strong policy guidance and support provided by Swedish policy makers throughout the period. Even before the Biofuels European Directive of 2003, the Swedish government was already proactive in stimulating ‘knowledge creation’ and ‘market formation’ for biofuels. The government support encouraged different ‘entrepreneurial experiments’ (F1) in 1st generation technology (wheat ethanol) and 2nd generation technology (wood ethanol). At the same time, stimulated by exogenous events such as strict environmental standards, Swedish local governments gave incentives for the development of buses run on ethanol, and the ‘market formation’(F5) of ethanol for public transportation. The successful project was later replicated for cars with the development of the flex-fuel technology for automobiles. The successful application of ethanol in the transportation market had the support and 'legitimation' from different advocates for the technology. It increased expectations about the prospects of biofuels in Sweden (F4), closing the loop for a positive cycle of innovation development of biofuels in the country. Hillman et al. (2008) point out the importance of the presence and fulfillment of all the functions as a pre-requisite for the successful performance of innovation in biofuels in Sweden, as compared to the Netherlands. The research also reveals the significance and the role of the function 'guidance of research' (F4) as a trigger of a positive cycle of development, or of a positive self reinforcing path. Hillman et al. (2008) and others from the same branch of literature validate the relevance of the seven functions of innovation as proposed by Hekkert et al. (2007) to explain the process of innovation of low carbon technologies (Marko P. Hekkert & Negro, 2009). However, the literature on the functions of innovation does not confirm whether the set of functions proposed explains the overall dynamics of the innovation process. The empirical literature confirms that the seven functions of innovation are necessary (Marko P. Hekkert & Negro, 2009), but they do not confirm whether they are sufficient to explain the process of innovation.

Bergek and colleagues (2004, 2008) propose an additional function of innovation named "Development of external economies". The authors claim that at the onset of the innovation process, an emerging TIS enlarges its scope of innovation by building a number of linkages with new actors who become active within the TIS. This dynamics creates opportunities for the TIS to generate positive externalities within the process of innovation, such as pooled labor work, a larger and high quality supply of intermediate goods, and increased flow of knowledge within the system (Anna Bergek et al., 2008; A. Bergek et al., 2008; Jacobsson, 2008; Jacobsson & Bergek, 2004). Most empirical research using the functions of innovation has not considered this function as an element to map the evolution of the dynamics of the innovation process (Anna Bergek et al., 2008).

As explained in the introduction, this dissertation follows the seven functions proposed by Hekkert et al. (2007) and, building on the function "Development of external economies" proposed by Bergek, it suggests an additional function of innovation, "Building of capabilities in the downstream market". The list of eight functions of innovation that follows describes each function, and provides examples to illustrate how the concept can be applied to the case of biofuel ethanol (for detailed list of examples of functions of innovation applied to ethanol, see appendix A - Codebook):

1. Entrepreneurship (F1): - Entrepreneurship involves risk and "learning by experimentation". The industrial/manufacturing sector plays the main role in entrepreneurial activities. Events that reflect growing industrial capacity, new projects and plants are all related to entrepreneurial activities. In the case of ethanol, it includes reports of events informing about a new ethanol plant, or expansion of ethanol production. Alternatively, the function may relate to events about downsizing of ethanol production. In this case, it has a negative sign.

2. Knowledge creation (F2): - it relates to R&D activities, and experience, and is directly linked to "learning by searching" and "learning by doing". Government, industry, and academia all play a critical role in knowledge creation. In the case of ethanol, knowledge creation consists of first generation technologies (starch and sugar feedstock) that have been available since late nineteen century. For 1st generation technologies, new knowledge relates more to experience and learning by doing, since the technology is considered mature. The generation of new knowledge is about process improvement, gains in cost, energy efficiency, and gains in productivity as well as scaling factors. The 2nd generation technology, on the other hand, is at the laboratory and pilot scale. Therefore, new knowledge relates more to research, development, and demonstration. Examples of the function of innovation applied to ethanol may include a new patent,

feasibility studies or new projects exploring new processes, R&D activities, developments and deployments to pilot and demonstration scale, and tests and feasibility studies using alternative fuels vehicles running on ethanol.

3. <u>Knowledge and information diffusion (F3)</u>: - individual and organization interaction are critical to fasten the pace of innovative activities. Collaboration among actors and institutions, and the formation of knowledge networks increase creativity and promote better use of resources. This function applied to biofuel ethanol may include events like conferences, workshops, meetings, or any event involving interaction, collaboration for information exchange.

4. <u>Guidance of research (F4)</u>: - this function relates to the research agenda, and represents the selection of technology options generated in the function knowledge creation (F2). It highlights the fact that technological change depends on choices made among different technological possibilities. Guidance of research relates to the notion that during the early stages of development, different technology possibilities compete for scarce resources within the innovation systems. Entrepreneurs, investors, and policy makers make decisions based on incomplete information. A set of inputs, data, and knowledge available in the market influence decision markers' perception and expectations about the different technology options available within the TIS (Anna Bergek et al., 2008; M. P. Hekkert, Suurs et al., 2007) Examples of reports of events relating to this function of innovation include reports of studies generating a positive expectation about ethanol, or studies reporting positive results of ethanol, or new legislation regulating/promoting the use of biofuel ethanol, or reports of positive results from tests with cars running on ethanol or blends of ethanol with gasoline. Alternatively, the function may also include negative reports of ethanol.

5. <u>Market formation and consolidation (F5):</u> - Policies that internalize environmental externalities and promote private investments in the supply and demand of renewables. Some might include: market reforms, public procurement, market obligations, cap and

trade policies, zero-emission vehicles, pricing of CO_2, and tax credits for renewables (Geller 2003). In the case of ethanol, they include mandates like the Renewable Fuel Standards (RFS).

6. Resource mobilization (F6): – it relates to financial and human resources allocated to the technology or product over time. It also includes financing through loan programs, low interest rates, subsidies, and investments to finance ethanol or flex fuel vehicles. Players include government, industry, and the financial sector.

7. Legitimation (F7): - this function has the goal to counteract the inertia intrinsic of most systems, where there is often a resistance to change. This function can be fulfilled by advocacy coalitions that lobby for the new technology, trying to influence the R&D agenda (F4), and funding activity (F6). It can be a lobby activity from politicians advocating for ethanol during a public speech, or the automobile sector asking government for additional investments in infrastructure for the distribution of high blend ethanol, or lobbying activities against biofuels, like the many taking place during the high profile debate about fuel versus food.

8. Building of capabilities in the downstream market (F8): - in the case of ethanol, this function reflects the development of competences in the distribution and automobile sectors, without which biofuels cannot win space in the downstream market. This function will map the development and commercialization of ethanol and flex fuel vehicles, and the infra-structure for distribution of biofuels. All technological and R&D activities are classified under knowledge creation (F2).

A Technological Innovation System is successful if all system functions are present and are fulfilled by the main components of the innovation system. It is important to notice that the eight functions presented are complementary to each other and are highly interdependent. Functions interact in a number of different and complex ways. For example, while knowledge creation is affected by guidance of research and resource allocation, market formation can be determined by legitimation, while influencing entrepreneurship. The ways the functions interact over time create dynamics of path dependence, generating virtuous cycles in the case of positive feed-back loops, or a vicious cycle when negative feed-backs are prevalent (Anna Bergek et al., 2008; M. P. Hekkert, Suurs et al., 2007; Hillman et al., 2008). Sometimes, the sequence of events describing the development of innovation leads to a self-reinforcing pattern of cumulative causation. The innovation systems develop from a formative to a market diffusion phase when this pattern becomes self-sustained and repetitive (Hillman et al., 2008).

TIS are not impervious to the external environment (ex. oil prices), and remain susceptible to external factors and events that can create opportunities to trigger mechanisms that will turn into virtuous or vicious cycles (Hillman et al., 2008). For example, both ethanol programs in the U.S. and Brazil were initiated at commercial scale in response to the 1973 Arab Oil Embargo. Likewise, the recent boom in R&D and production of ethanol has been stimulated by the steep increase in oil prices. Therefore, the analysis must contemplate those external factors and be able to identify how the system is affected by them over time.

The functions of innovation is a framework in development. The set of functions presented has been tested empirically, and the literature reviewed shows that although relevant and necessary, the list of function may not explain the complete dynamics of innovation processes. Some critics argue against the functionalist approach based on early versions of the framework (B. A. Lundvall, 2007). The functions of innovation systems should be assessed in light of the recent literature that places innovation within the context of sustainainable and low carbon technologies. The framework preserves the core concept/assumption of the more traditional strand of the literature on innovation systems: 1) a TIS has different tasks or functions; 2) its most important task is learning (by experimenting, by doing, by searching, by interacting, by using); and 3) its ultimate goal is to promote the development, diffusion, and the adoption of new knowledge.

CHAPTER 3
LEARNING AND TECHNOLOGICAL CHANGE

This chapter explores the different mechanisms of learning, and how they relate to technological change. By using the cases of ethanol in the U.S. and in Brazil, it shows that learning (research, development, demonstration, experience, interaction with the group, adoption of routines, feedback from downstream and upstream) has a positive impact on production cost, energy use, and carbon footprint of ethanol production processes. The chapter's main goal is to show that technology is dynamic over time, and that appropriate policies may induce the adoption of technologies that not only contribute with knowledge, but also with environmental gains to society.

3.1 The case of biofuel ethanol in the U.S.

Interest in renewable fuels in the U.S. began during the 1970s, in reaction to the Arab Oil Embargo, and the fall of the shah of Iran (Bettelheim, 2006). The phasing out of lead as an octane enhancer by the late 1970s sparked some interest on the use of ethanol as a fuel additive. In 1978, the National Energy Act gave federal tax exemption to gasoline containing 10% ethanol (US DOE, 2000).

Ethanol production has been increasing steadily, growing from 3 billion gallons in 2003 to 10.5 billion gallons in 2009 (fig. 3). Government mandates[15] and tax incentives are the main reason for high volume output (RFA, 2009; US DOE, 2009). Corn-based ethanol accounts for the largest share of renewable fuels production and consumption in

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[15] The Energy Independence and Security Act of 2007 (EISA 2007) renews the renewable fuels standard (RFS) established by the Energy Policy Act of 2005, and mandates the consumption of 36 billion gallons of biofuels in 2022. It requires that 21 billion gallons be "advanced biofuels" - biofuels that don't use corn as a feedstock and reduce GHG emissions in 50% when compared to gasoline (Capehart, Schnepf, & Yacobucci, 2008; RFA, 2009; Sissine, 2007).

the United States, where it serves mostly as oxygenate[16] blended into gasoline at 10% by volume, marketed as E10 or "gasohol". According to the Renewable Fuels Association[17], ethanol installed capacity as of January 2010 was at 12.0 billion gallons per year.

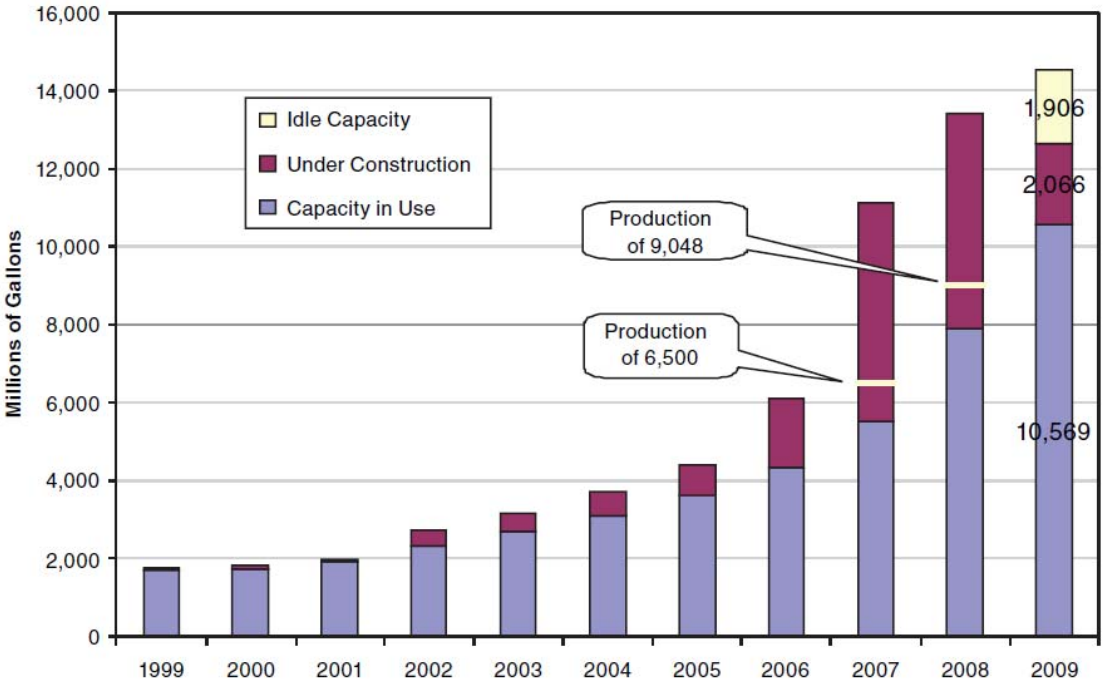

Figure 3: U.S. Ethanol production and capacity. (National Academies of Sciences, 2010 – based from workshop presentation by Tiffany, University of Minnesota, June 24, 2009) available at nap.edu/catalog/12806.html

16 Replacing methyl tertiary butyl ether (MTBE), an oxygenate that started to be phased out in 1999, following recommendations from the EPA.

17 http://www.ethanolrfa.org/

3.1.1 Technology, production/supply

The main feedstock for ethanol production in the United States is corn (>95%). Other sources include grain sorghum, barley, wheat, and cheese whey (RFA, 2009). During the last three decades, corn productivity almost doubled in bushels per acre (USDA ERS, 2007), as a result of innovation in fertilizers, pesticides, seeds, agricultural management, and mechanization (fig.4).

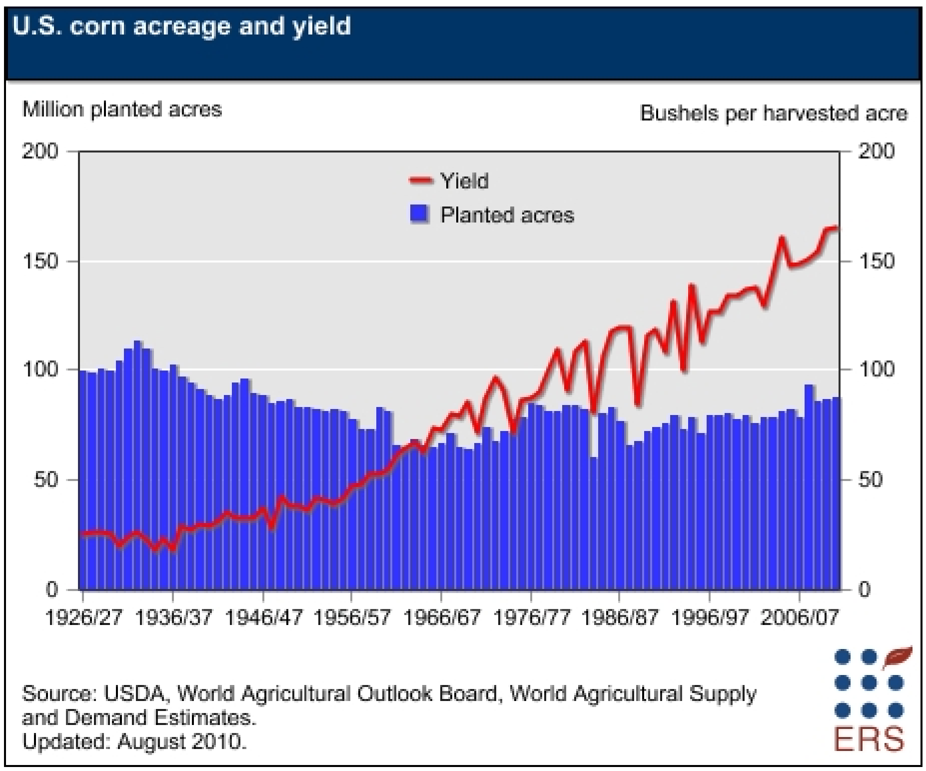

Figure 4: U.S. corn acreage and yield (USDA-Economic Research Service - http://www.ers.usda.gov/Briefing/Corn/background.htm)

The U.S. is the world largest producer of ethanol for the transportation sector, but the overreliance on corn has raised questions over the long term impact of growing corn crops to agriculture and environment in the U.S. (Malcolm, Aillery, & Weinberg, 2009). In 2007/2008, fuel ethanol plants used around 25% of U.S corn as a feedstock, a significant increase compared to previous years (fig.5). The growing demand of corn for fuel has sparked debate over the use of edible crops to serve the industry of fuels for transportation in detriment of world demand of food (Earley & Mc Keown, 2009; RFA, 2009). The fuel versus food debate evolved between 2006 and 2008, when the world grain market experienced an increasing demand, with commodity food prices reaching unprecedented levels. The food grain and commodity boom of 2007 – 2008 coincided with a spike in energy prices, when oil prices jumped to US$133 a barrel. The food grain and commodity boom also coincided with high biofuels production and growing corn use for ethanol production in the United States. During the time, corn ethanol was blamed for the high price levels and food security problem. However, a recent World Bank report reveals that biofuels had a minor impact in the boom in commodity prices. The most important factors leading to more expensive food grains were higher energy prices, adverse weather conditions, the weak dollar, export bans established for some commodities and low investment in food commodities (Baffes & Haniotis, 2010).

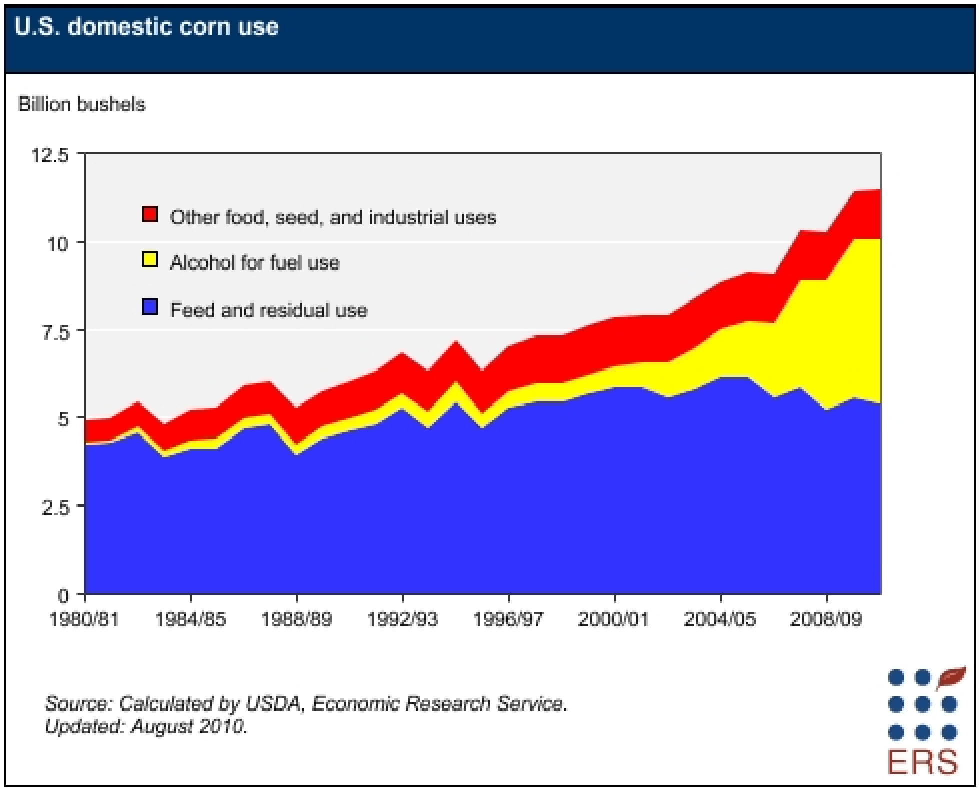

Figure 5: Use of corn grain in the U.S. (USDA – Economic Research Service - http://www.ers.usda.gov/Briefing/Corn/background.htm)

Corn grain-based ethanol uses a conventional technology that first converts the corn (starch) to sugar, and then ferments the sugar into ethanol. The process grinds the corn kernel following a dry or wet milling process. Currently, most plants in the U.S. use the dry milling process. This process produces a by-product called dried distillers grains (DDG) that is consumed by the animal feed industry. In the corn grain-based ethanol process, only the starchy part of the corn is used in the conversion to sugar, representing only a small part of the plant.

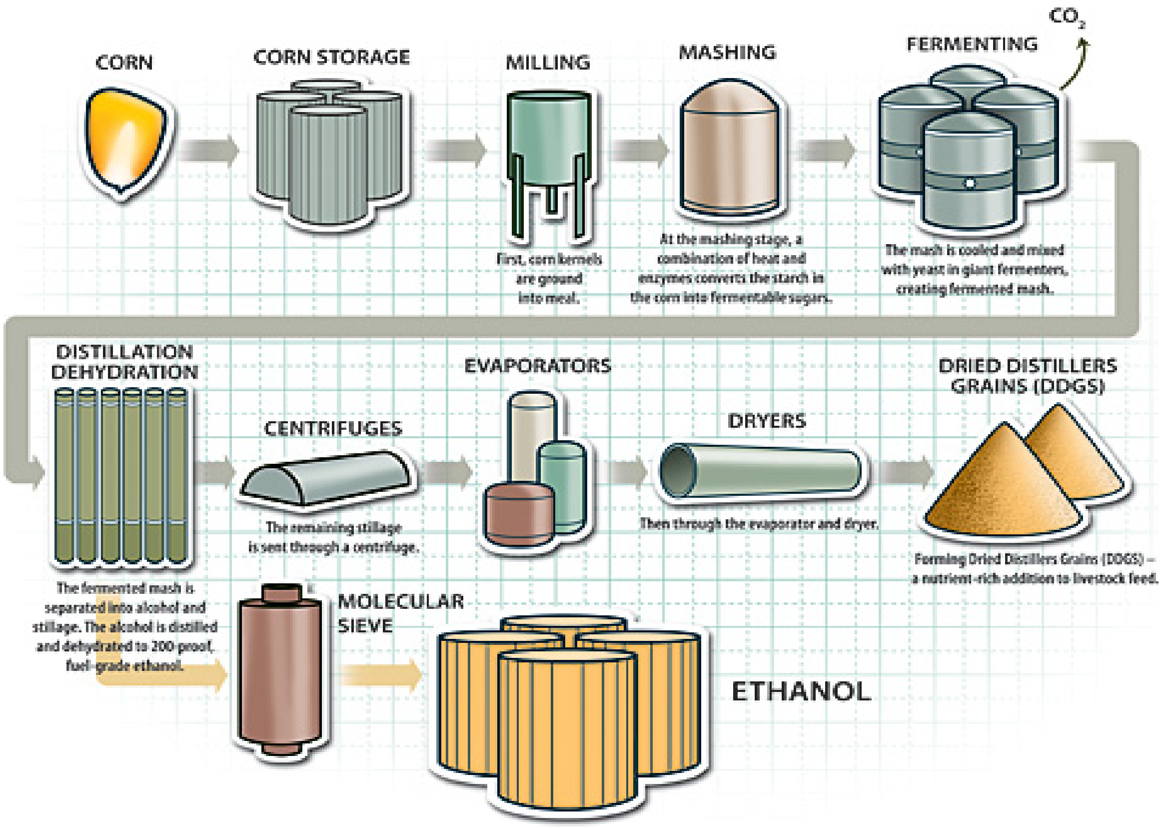

Figure 6: Corn ethanol production – dry milling process (VeraSun Energy)

Since a large portion of ethanol producers is not verticalized, ethanol plants tend to be located near corn cooperatives to minimize the transportation cost of feedstocks (Hettinga, 2007; Hettinga et al., 2009). For this reason, most corn ethanol plants are located in the Midwest.

The conventional process to produce ethanol uses only the starchy part of the corn, leaving the corncob and straw on the crop field. More advanced processes, those not using feedstocks that compete with food, use cellulosic materials. The process to convert cellulose materials to sugar is more difficult, and research is ongoing to make the cellulosic ethanol technology competitive. The Farm Bill 2008 confers a tax credit of $1.01/gal to blenders consuming ethanol using cellulose-based feedstocks. It also funds R&D, provides loans and grants for production of cellulosic ethanol. Many demonstration plants of cellulosic ethanol are already in operation in the U.S. (Royal Society, 2008; WorldWatch_Institute, 2006). Twenty eight projects of advanced/cellulosic ethanol are in development, using a diversified number of biomass materials (RFA, 2010). Since these processes use feedstock other than corn, industrial plants don't need to be geographically close to corn production. The use of a diversified source of biomass feedstocks allows for planning and construction of plants close to biomass production and big consuming centers of fuels (EERE/Biomass, 2009; RFA, 2010).

3.1.2 Technological change contributes to low production costs

The use of crop-based fuels to power automobiles in the U.S. dates from the beginning of the twenty century when Henry Ford developed the Model-T using ethanol as a fuel (Bernton, Kovarik, & Sklar, 2010). Since then, corn-based ethanol has made significant progress. Table 1 and Table 2 below show that production costs have improved over the last decades thanks to gains in corn and ethanol yield, scale, lower enzyme costs, fermentation technology, and better utilization of energy throughout the process (see Hettinga 2007 and Hettinga et al. 2009 for a complete and more technical review). Feedstock (corn) and energy (fossil fuels and electricity) represent the largest portion in the industrial cost structure of an ethanol plant today[18].

Table 1: Corn production 1980 - 2005. From Hettinga et al. 2009

Corn	1980-1985	2000-2005	% Change
Yield (ton/ha year)	**6.5**	**8.9**	**+ 37%**
Production (million ton/year)	**185**	**260**	**+40%**
Average farm size (hectares/farm)	**40**	**80**	**+100%**

[18] Excluding capital recovery costs, taxes, insurance, and land rent.

3.1.3 Technological change contributes to less energy consumption

It has been argued in Chapter 2 that the process of technological change is endogenous, that is, it is not only influenced by time and market prices, but by historic factors internal to the innovation process (Popp et al., 2009). Innovation in energy systems is also influenced by policy and business decisions on research and development, and by firms' strategic decisions to take advantage of market opportunities. Learning and knowledge production and diffusion are critical in the process of technological change and innovation. Knowledge can be acquired in different ways and in different forms: 1) codified knowledge, the one that is explicit in documents, publications, and patents, is normally acquired through activities of research, development, and demonstration; and 2) tacit knowledge, the one that is often implicit in routines, it is normally acquired by cumulative experience, by using the technology, and by receiving feedback from technology users (Jensen, Johnson, Lorenz, & Lundvall, 2007). Research and development activities contribute to learning by searching; time, experience, and implementation of better manufacturing routines characterize learning by doing; and feedback from external markets/users of technology are specific to the processes of learning by using and interacting (IEA, 2000; Kohler, Grubb, Popp, & Edenhofer, 2006).

Improvements in corn ethanol technology can be explained by learning by searching (applied R&D and deployment of efficient processes), learning by doing (experience over time, improved manufacturing routines), and exchange of information with technology users (learning by using and interacting) (Hettinga, 2007). The pressure in energy costs (especially during the late 1990s and early 2000s, when oil prices became more volatile) helped justify investments in energy efficiency for ethanol production. The average consumption of energy has been cut in half in the last twenty five years, going from approximately 22 MegaJoule (MJ) per liter of ethanol produced in the 1980s to around 10 MJ per liter in an average ethanol plant today. Still, energy accounts for more than half of the industrial costs in the plant.

Table 2: U.S. Ethanol conversion 1980 - 2005: From Hettinga et al. 2009

Ethanol	‘000$(2005)/liter 1980s	‘000$(2005)/liter 2005	% Change
Energy costs	140	70	-50%
Labor costs	55	16	-71%
Enzyme costs	40	10	-75%

3.1.4 Technology and the environmental impact of ethanol

The evidence shows that cumulative experience and R&D have had a positive effect on the environmental impact of ethanol. Energy use is one component of the environmental impact of corn ethanol. Energy use in ethanol plants vary with the process (dry or wet mills), with the scale of production, and with the technology used to heat and power plant operation. Most ethanol plants built after 2004 include investments in technologies that optimize utilization and recovery of heat. The implementation of fractionation as a feedstock pre-treatment before fermentation is another technology that is already bringing cost and energy efficiency advantages in the production of co-products ((S&T)2ConsultantsInc., 2009). Finally, site locations close to animal feedstock operations may reduce the need to dry distiller grains with solubles (DGS)[19], bringing greater returns on investment in energy savings and operational costs (Bevill, 2008; Kram, 2007; Morey, Tiffany, & Hatfield, 2006).

[19] Distillers dried grains with soluble (DDGS) are co-products of biorefineries that use the dry process for ethanol production. With high protein content, they have a market for livestock feed. With increased volumes of production of ethanol, there is a growing supply of DDGS.

Growing production of corn-derived ethanol has generated a market for the co-product distiller grains with solubles. Distiller grains (DGS) became a biomass fuel with potential to replace natural gas. Large volumes and consequent lower prices have helped DGS compete with volatile prices of natural gas during the last years, leading some producers to recycle DGS and burn it to generate electricity and process heat (Morey et al., 2006).

Wang et al. (2007) estimate energy use for different technology scenarios of ethanol plants. Results of the study show that the implementation of Combined Heat and Power (CHP), reduction in drying operation of distiller grains and solubles (DGS), and use of biomass for heat generation bring greater energy efficiency, and therefore significant environmental contribution in terms of GHG emissions, compared to plants fueled by coal or natural gas (Wang, Hong, & Huo, 2007). Figure 5 shows the impact of different technologies in the total consumption of fossil fuels in corn ethanol plants. The use of biomass to generate steam for the process provides the highest contribution. The new technology using natural gas without drying DGS consumes a little over half the energy consumed by a plant powered by coal. Results illustrate that low carbon innovation applied to a conventional process of corn-based ethanol can still bring economic and environmental gains. The use of biomass brings even larger economic and environmental gains.

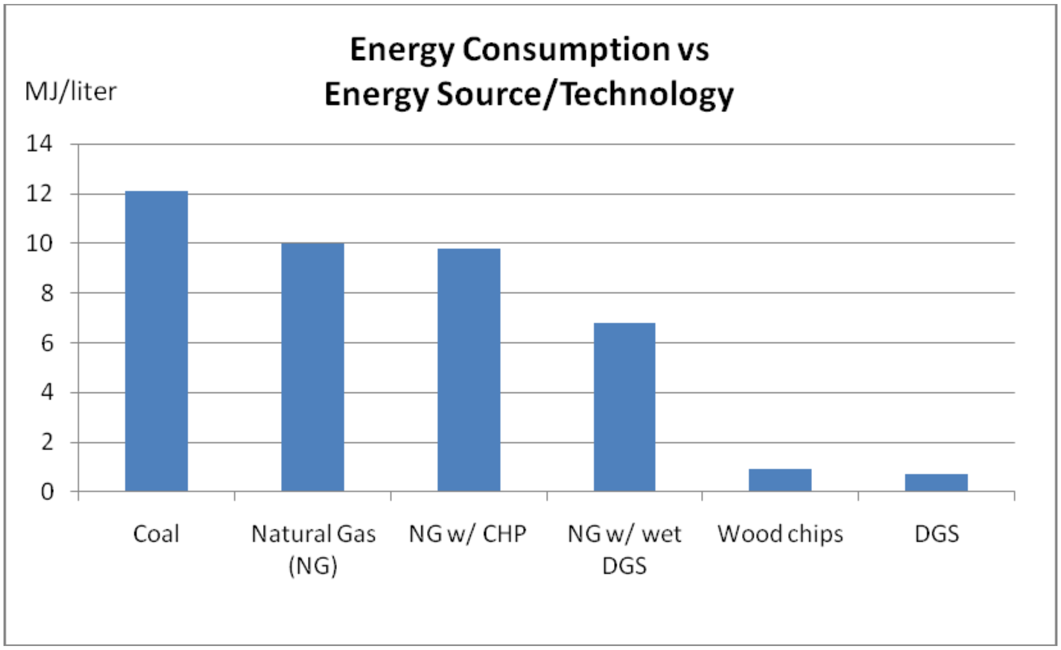

Figure 7: Corn Ethanol – Energy Consumption for different technologies (Wang et al. 2007)

Most recent biofuels policies recognize the positive impact of innovation on the environmental impact of corn ethanol. They also recognize the long term limitations of using edible feedstocks to produce biofuels. The Energy Independence and Security Act 2007 (EISA 2007) establishes a cap of 15 million gallons a year for corn ethanol use and requires the increasing production and consumption of advanced or cellulosic ethanol, using biomass materials that don't compete with food (fig.6). The policy's main goal is to direct technological change towards more sustainable forms of production of biofuels (Koshel & McAllister, 2010). EISA 2007 requires greenhouse gas emissions thresholds, demanding an improvement in relation to the baseline measures of gasoline and diesel emissions. New (after enactment of the law) production of corn ethanol (beyond 15 billion gallons/year) must reduce GHG emissions in 20%; cellulosic biofuels have a threshold of 60% GHG emissions; advanced biofuels (any biofuel other than corn ethanol) must meet a threshold of 50%; and advanced biodiesel must reduce GHG emissions in 50% compared to the diesel baseline.

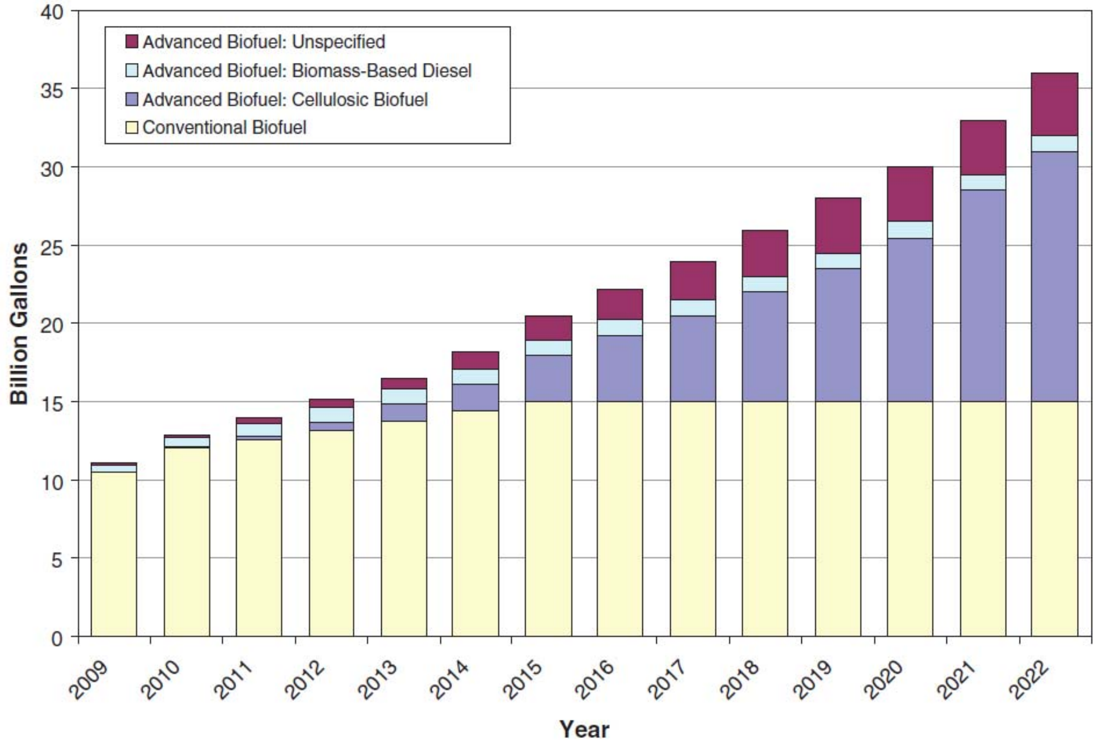

Figure 8: Volumes required by RFS2 under EISA 2007. Source: Environmental Protection Agency, Office of Transportation and Air Quality. Workshop presentation, June 23, 2009, available at (Koshel & McAllister, 2010)

Under EISA 2007, the EPA must perform a lifecycle analysis[20] to determine whether the different biofuels meet the GHG thresholds required by law. The calculations[21] take into account the different technologies used to produce corn ethanol, as illustrated in the figure below.

Consistent with (Wang et al., 2007), the EPA calculations (Fig. 9) recognize that under a period of 30 years, the conventional technology to produce corn ethanol (using natural gas and dry mill process) decrease GHG emissions by 17% compared to the

[20] A measure of total emissions of greenhouse gas emissions related to the total cycle of production of the fuel, including those related to feedstock production and respective inputs.

[21] The calculations take into account direct and indirect land use change resulting from additional crop planting, and assume GHG emissions impact over 100 years, discounting future emissions at a rate of 2% per year.

baseline of gasoline; the worst case scenario (using coal to power ethanol dry mill process) increases GHG emissions in 12%, and the best case scenario (using biomass, wet DGS, and combined heat and power), decreases GHG emission by 48% on average (including direct and indirect land use change) (EPA, 2009). Although there is still debate on the science that calculates life cycle analysis including direct and indirect land use change, it is certain that targeting ethanol technological progress towards less energy intensive technologies has a positive impact in the carbon foot print of ethanol production. The positive environmental impact represents a positive externality with positive social benefits greater than private benefits. Thus, these efficient technologies tend to be undersupplied by the market. In these cases, government intervention is justified to make sure the private sector supplies the optimal amount of efficient technologies for ethanol, therefore maximizing the benefits for society (Popp et al., 2009; Stern, 2007).

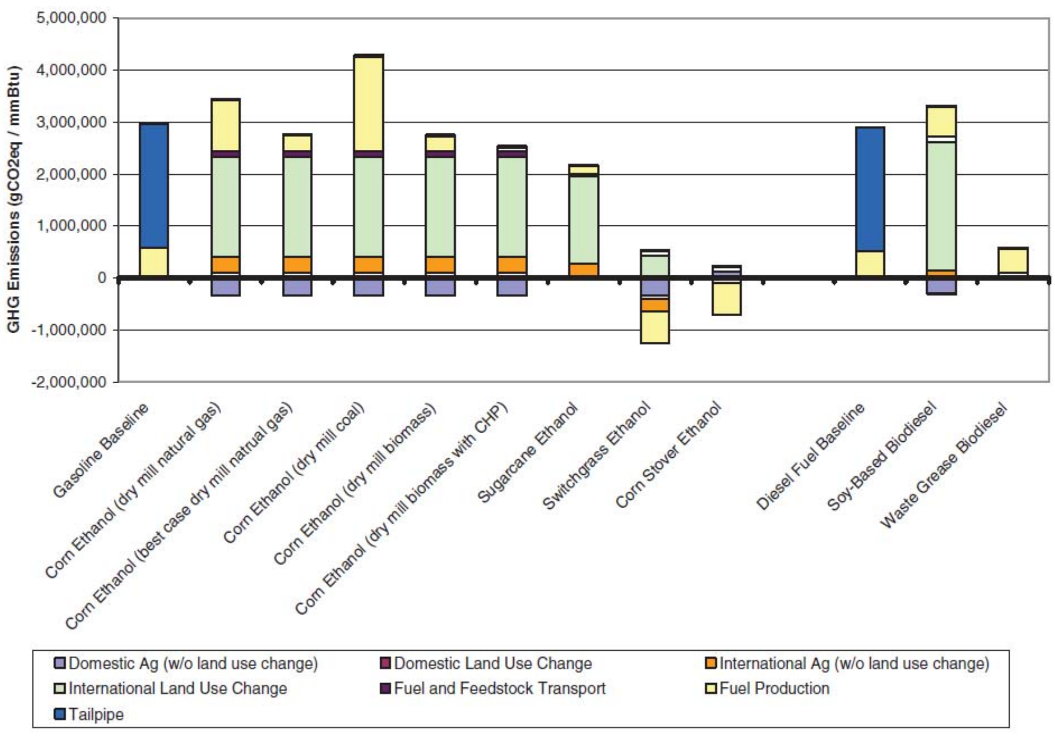

Figure 9: Life cycle greenhouse gas emissions (30 years, 0% discount rate). Calculated by EPA. Source: Env.Protection Ag., Office of Transp. Air Quality, Feb.2010, EPA-420-F09-024.

3.2 The Case of Biofuel Ethanol in Brazil

Ethanol in Brazil is produced from sugarcane, a crop very well adapted to the country's abundant land and tropical climate. Brazil is the pioneer and the most competitive producer of sugarcane ethanol worldwide, mainly due to its natural endowments, its long tradition in the sugar industry, and the technological progress made in the agricultural and industrial conversion processes, allowing significant increase in production over time (J. Goldemberg, Coelho, & Lucon, 2004). Between 1975 and 2004, sugarcane productivity grew 2.3% annually, while ethanol productivity (from sugarcane) jumped at a rate of 1.17% per year (Martines-Filho, Burnquist, & Vian, 2006). From 1975 to 2000, ethanol yield per hectare of sugarcane increased from 535 to 1585 gallons (Arraes, 2006).

According to the Brazilian Sugarcane Industry Association (UNICA)[22] , production reached 6 billion gallons (in approximately 400 industrial plants) of ethanol in 2008, against 0.9 billion gallons in 1980. Back in 1980, the cost to produce ethanol was approximately three times as high as the international cost of gasoline, justifying strong government subsidies. By 2004, ethanol prices were able to compete with gasoline without government intervention (J. Goldemberg, 2007, 2009). Today, many sugarcane mills also generate electricity from bagasse, an industrial by-product, improving the energy balance, and reducing even further the cost of production (IAEA, 2006). Higher gasoline prices and larger industrial scale gave the Brazilian ethanol enough leverage to compete with gasoline at international prices (J. Goldemberg, 2007).

[22] www.unica.com.br

3.2.1 Technology

Sugarcane cultivation and ethanol production concentrate in the Center-South region of Brazil (85%), especially in the state of Sao Paulo (60%), benefiting from high labor skills and strong infrastructure (BNDES & CGEE, 2008; J. Goldemberg, 2009; R. C. Leite, 1990). Most research is concentrated geographically in the Southeast, with important initiatives led by government, private, academic, and hybrid forms of institutional arrangements.

Sugarcane is a semi-perennial tall grass that grows well in tropical zones. Brazil is the largest and most productive sugarcane grower, accounting for more than 40% of the world production (BNDES & CGEE, 2008). In Brazil, sugarcane has on average a six-year production cycle, after which a new crop is replanted. Brazil's average productivity is around 70 and 80 ton per hectare, but productivity in the Center-South can reach up to 90 ton/ha of sugarcane in some farms depending on the season (BNDES & CGEE, 2008). Sugarcane consumes low rates of fertilizer, because most industrial plants recycle vinasse (sugarcane industrial waste rich in nitrogen) to the field. Sugarcane cannot be stored, and needs to be crushed immediately after the harvest. Brazil has 340 million hectares of total agricultural land, from which 77 million are still available as cropland. Sugarcane occupies 7 million hectares, from which 4 million for ethanol production (J. Goldemberg, 2009; R. C. D. Leite, Leal, Cortez, Griffin, & Scandiffio, 2009).

In Brazil, ethanol is produced as anhydrous (dehydrated) ethanol to be blended with gasoline (E20 – E25), and as hydrated ethanol – 6% of water in weight - (E100) to be used in dedicated engines or in flex fuel vehicles (FFV). Because it requires one less operation (dehydration), dehydrated ethanol tends to be less expensive than anhydrous ethanol (BNDES & CGEE, 2008). A simplified industrial process to convert sugarcane to ethanol is shown below.

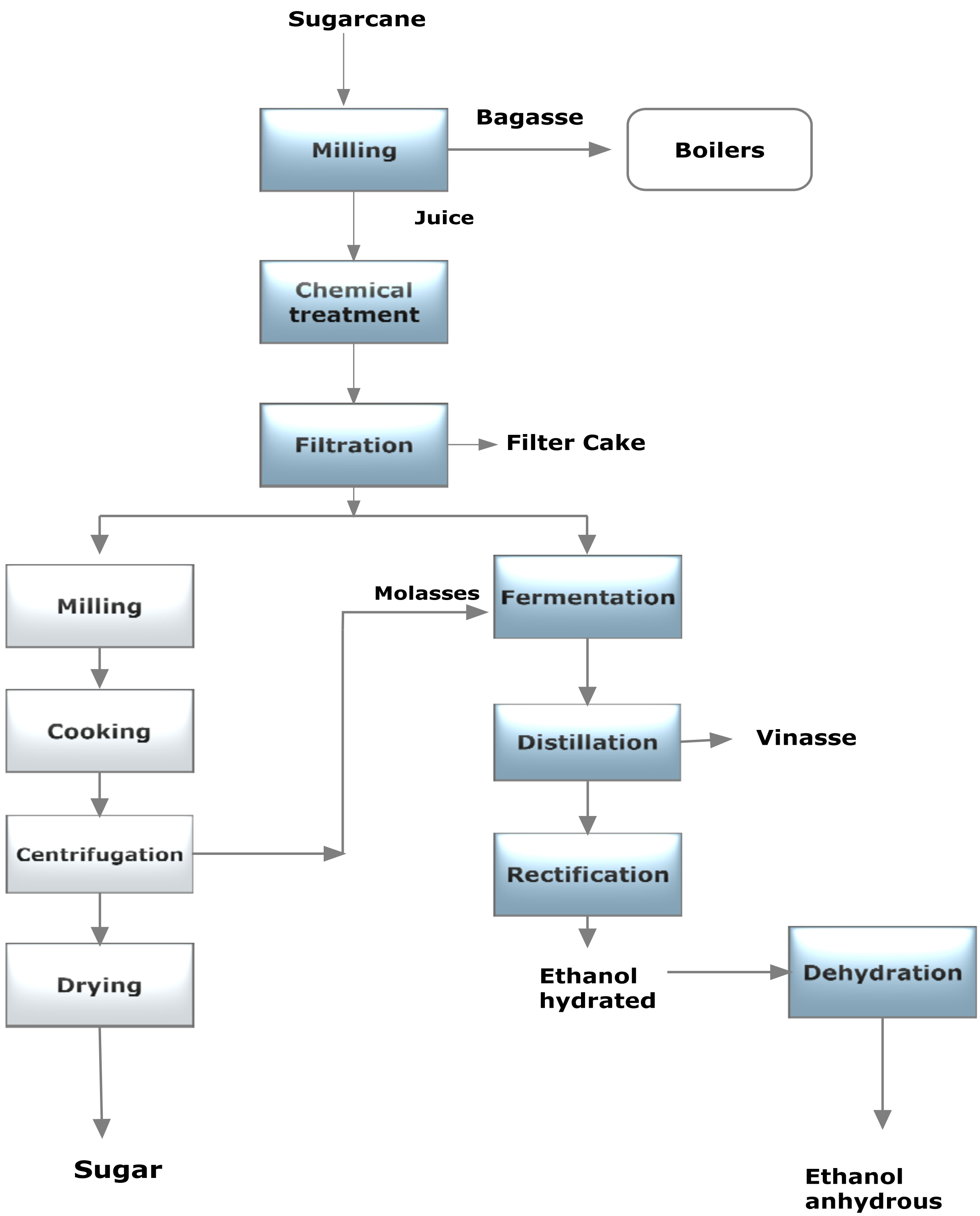

Figure 10: Conversion of Sugarcane to Ethanol in Brazil (BNDES & CGEE 2008), based on Seabra (2008)

Brazil's ethanol program dates from 1975, when the military government initiated a mandatory use of the biofuel in response to the international oil crisis (Moreira & Goldemberg, 1999). The launch of the National Alcohol Program – Proalcool - was a component of a large Energy Strategy Plan under the import substitution model seeking to decrease the country's dependence on external sources of energy (R. C. Leite, 1990). Proalcool also served the interests of sugar producers, who had been threatened by strong decline in international sugar prices at that time[23] (Geller, 2003; IEA, 2006; Sandalow, 2006).

During the first period of the alcohol program, government, universities, and the sugar industry focused efforts in scale of production and productivity. More recent investments in R&D – public and private – led to the sequencing of the genetic code of sugarcane. With more than 500 different crop varieties, farmers were able to adapt their crops to different climate and terrain conditions[24]. Brazil also is an international player in the R&D of second generation ethanol production[25]. The Center for Sugarcane Technology, a private research institute supported by Brazilian ethanol producers, has played an important role in promoting R&D throughout much of the history of ethanol development. The practice of residue recycling to the sugarcane field (filter cake and vinasse), as well as continuing research on different varieties of sugarcane contributes to decreasing rates of fertilizer and water use.

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[23] Ethanol was first produced as a co-product in the process of sugar production from sugarcane.
[24]The genetic coding of sugarcane was developed by CTC, Agronomic Institute of Campinas, and RIDESA (Rede Interuniversitaria para o Desenvolvimento do Setor Sucroalcooleiro), a network of 8 federal universities.
[25] A network of 15 universities and research institutes participate in the development of cellulosic ethanol from sugarcane bagasse, among them University of Sao Paulo, University of Campinas, Federal University of Rio de Janeiro, Federal University of Brasilia, Federal University of Pernambuco, IPT /SP, and University of Lund in Sweden (Ereno, 2007).

During the last three decades, ethanol productivity grew at an average annual rate of 1.4% in agriculture (sugarcane production) and 1.6% in the industry (ethanol production), providing an overall average annual productivity growth of 3.1%. Figure 9 illustrates this long term trend (BNDES & CGEE, 2008).

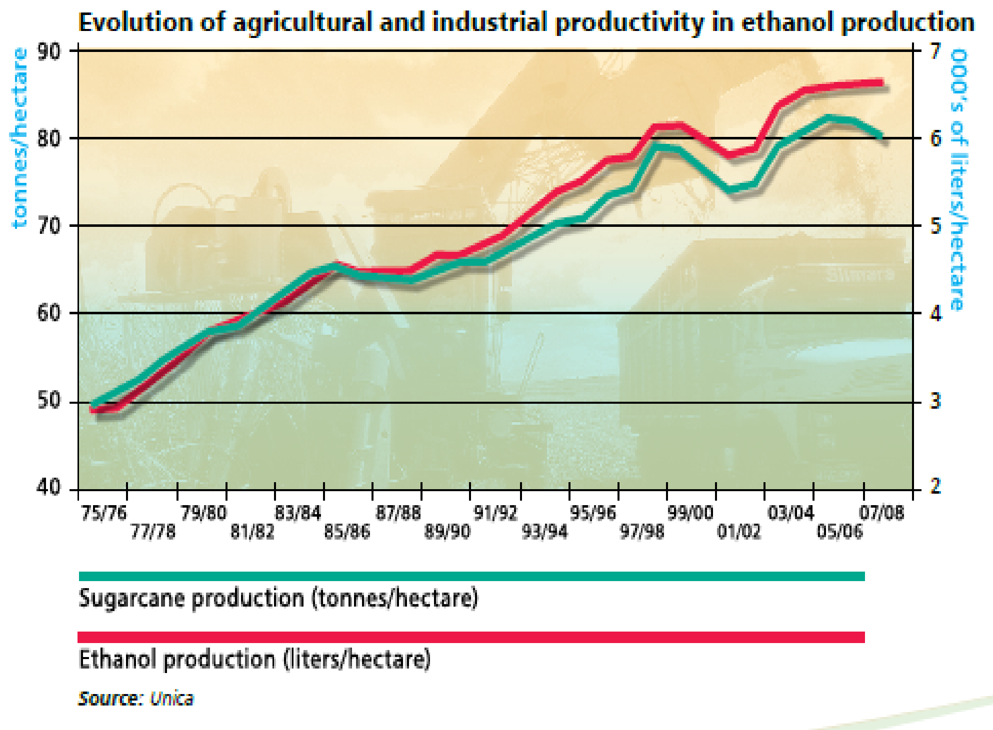

Figure 11: Ethanol and Sugarcane productivity. Source: Ethanol and Biopower (2009). Available at UNICA (www.unica.com)

Sugarcane and ethanol have gained competitiveness with improvements made by R&D, engineering, and experience. Research was critical to develop new varieties of sugarcane; new agriculture technologies helped to improved sugarcane harvests; and progress in engineering brought considerable gains in industrial operations such as juice extraction, fermentation and distillation (Bake, Junginger, Faaij, Poot, & Walter, 2009; Moreira & Goldemberg, 1999). Scale was an important factor helping to reduce cost of production of ethanol in Brazil. The total cost to produce ethanol reduced significantly during the last thirty years, from US$ 0.98 per liter of hydrated in 1975 to US$ 0.26 – US$ 0.305 in 2004 (Bake et al., 2009). Cost reductions of ethanol in Brazil can be understood by breaking the process in two main steps: agricultural and industrial.

Agriculture – sugarcane production

Sugarcane is a large component of the ethanol cost structure, accounting for approximately 60% of the total cost of production. Increasing the competitiveness of sugarcane has always been a constant goal of the ethanol industry in Brazil. This motivation attracted investments to improve the quality and decrease the cost of the feedstock over the years. In addition to investments in R&D to create new sugarcane varieties, the industry invested in agricultural management, logistics, and transportation to improve overall efficiency (Bake, 2006; Bake et al., 2009; Rosillo-Calle & Cortez, 1998).

Maximizing the rate of sugars in the sugarcane juice before it goes into fermentation has been one of the main technological and economic goals in the process to convert sugarcane to ethanol. The higher the total reducible sugar (TRS) contained in the sugarcane, the better the rate of fermentation in the industrial process. Therefore, the industry made efforts towards improving the amount of sugarcane harvested per hectare, and towards maximizing the TRS for a given quantity of sugarcane. The amount of sugar in sugarcane depends on the climate and soil conditions, but investments in new varieties of sugarcane were critical to improve the TRS over time. Another factor contributing to higher levels of sugarcane productivity was the length of the ratoon system. The increase in the number of years before a new planting cycling would begin (longer ratoon system) reduced the cost of soil preparation, and crop maintenance. Increasing sugarcane yields (normally measured in tons of cane per hectare per year) also reduced the cost of harvest, and the cost of the land. For a detailed analysis of sugarcane cost structure, and its evolution over the years, see Bake (2006).

Table 3: Sugarcane productivity. Source: Bake et al. 2009

Sugarcane (Brazil)	1975 - 1980	2000 -
Ratoon system (years)	3 - 4	5 - 7
Agricultural yield (TC/ha/year)	65 - 72	75 - 82
Agricultural yield (kg TRS/TC)	124 - 128	144 - 148

<u>Industrial – conversion of sugarcane to ethanol</u>

Scale was a critical contributing factor to reduce industrial costs. Scale affects industrial yield, reduce investment and operational costs. Larger plants lead to higher load factors, more automation, less stops, and more process optimization. The scale also required more efficient and continuous operations throughout the process. The industrial process benefited from gains in fermentation time, purity of juice, and R&D to find new yeasts to increase the efficiency of the continuous fermentation process. Between 1977 and 2000, the fermentation time has been cut by 40%; the percentage of ethanol after fermentation has doubled, and the overall fermentation efficiency increased from 83 to 91.4 (Bake 2006, based on data from CTC). Overall, during the last thirty years, the amount of ethanol produced in liters per hectares of sugarcane harvested doubled from approximately 3,000 to 6,000 liters of ethanol per hectare (J. Goldemberg, 2009).

<u>Ethanol and Bioelectricity</u>

In energy terms, sugarcane is made of one third sugarcane juice (for the production of ethanol), one third bagasse (from sugarcane crushing), and one third straw (left in the field). Sugar and ethanol producers generate 98% of their energy needs from sugarcane bagasse. The use of bagasse as energy source replaces expensive fossil fuel, and contributes to the carbon footprint of the sugarcane ethanol production process (Wang, Wu, Huo, & Liu, 2008). Currently, it is becoming a growing revenue source for ethanol producers. The Brazilian regulatory framework during the 1990s didn't give enough incentives for producers to invest in more efficient and high pressure boilers. The current policy scenario offers more incentives for production and sale of electricity as a co-product in the process of sugarcane conversion (J. Goldemberg, Coelho, & Guardabassi, 2008). The eradication of the practice of pre-harvesting burning in sugarcane fields - in compliance with the "Green Protocole" of 2014 – will increase the supply of sugarcane straws[26] for biopower production[27] . In the short and medium term, biopower will become a strategic commercial product for ethanol and sugar producers, and a potential source of alternative energy in the populated Center-South region of Brazil (Castro, Brandao, & Dantas, 2009).

3.2.2 The Environmental impact of sugarcane ethanol

In February 2010, the Environmental Protection Agency announced the final regulation of the Renewable Fuels Standards (named RFS2), considering sugarcane ethanol an advanced biofuel, or a biofuel reducing greenhouse gas emissions in at least 50% compared to the baseline emissions of gasoline (EPA, 2009). According to EPA, sugarcane ethanol reduces GHG emissions by 61%[28] compared to baseline gasoline emissions, considering 30 years for calculations of the effects of indirect land use effect.

[26] When mechanical harvesting is not possible, sugarcane fields need to be burned before harvest, and the straws are wasted in the fields.
[27] Today, around 50% of sugarcane harvest is mechanized in the state of Sao Paulo.
[28] The numbers published in February 2010 were revised after the EPA took into consideration several comments submitted for appreciation. More details are available at http://www.epa.gov/otaq/fuels/renewablefuels/index.htm.

3.3 Conclusion

This chapter argues that technology is endogenous to the innovation system, and changes with R&D and learning over time. The cases show that over time, technological change has had a positive effect on the environmental impact of ethanol. It shows that learning activities (learning by searching, by doing, by using, and by interacting) have contributed to technological progress and environmental sustainability of corn and sugarcane ethanol. More recently, higher energy prices and biofuels policies induced more sustainable technological change. While the basic corn ethanol technology provides GHG emissions benefits of 21% on average, the adoption of more advanced technologies in ethanol plants improves the benefits to 48% in relation to gasoline, on average. This environmental benefit gap in corn ethanol shows that given appropriate policies and technologies, the U.S. can decrease the carbon footprint of corn-based ethanol. The Brazil case shows that the use of bagasse to power sugarcane ethanol plants brings environmental benefits that can still be improved when ethanol plants start selling the surplus power from burning ethanol straw to the grid. The next chapters will explore in more detail the dynamic features of technological change, using the functions of innovation to assess the innovation trajectories of ethanol in the U.S. and in Brazil.

CHAPTER 4

DATA, CODING, AND METHODOLOGY

This study assumes that the functions of innovation perspective is a causal and evolutionary framework that cannot be tested by an independent/dependent variable relationship, but rather by a mechanism of path-dependency, with multiple causes and outcomes, or a sequence of causal relationships with self-reinforcing characteristics (Gerring, 2001). Therefore, explanations of outcomes are based on patterns of temporal and geographical variation of functions of innovation, such as positive (virtuous cycles) and negative (vicious) feedback (Pierson, 2003). By plotting the evolution of functions over time, I expect to identify the patterns of development for each function, and the emergence of positive and negative feedback, providing support for a comparative analysis between the U.S. and Brazil.

4.1 Definitions and assumptions

To map the innovation process, one needs tools to measure and to understand how innovation takes place. Van de Ven et al. (2000) and Poole et al. (2000) use “process theory” in contrast to “variance theory” to suggest methods to study how phenomena evolve over time. According to the authors, “a theory of innovation is fundamentally a theory of change in a social system” (Poole et al., 2000; Van de Ven & Poole, 2000). While innovation may be related to the introduction of a new concept or idea, the process of innovation relates to the chain of events that represent how people interact to develop and implement new concepts and ideas over time. Therefore, events are assumed to represent instances when change is observed within the innovation system. In this research, change relates to the longitudinal change in the functions of innovation systems of biofuels, or in the context influencing change over time. For example, the completion of a research project that leads to a technical conclusion in relation to biofuels is an event where change in knowledge creation occurs. There are different methods for observing change over time.

This research uses published information that brings historical data from which it is possible to form a sequence of events related to the development of ethanol as a biofuel in the U.S. and in Brazil. Since past events cannot be observed in real time, the analyst may use bibliographic databases as a data source to identify events in the innovation of ethanol over time (Van de Ven & Poole, 2000).

4.2 Data

As explained in the introduction, since ethanol represents most of biofuels produced in the U.S. and in Brazil, this study focuses on the development of ethanol, and will exclude biodiesel and other fuels derived from biological sources. The years considered span from 1975 (just after the 1973 Arab Oil Embargo) to 2008. The research builds on multiple public sources that report on the set of historic events that helped determine the development paths of biofuels industry over time in each country. Because Brazil has limited coverage in international databases, especially during the 1970s, 1980s, and 1990, the Brazilian newspaper O Estado de Sao Paulo is used as the main source reporting on Brazilian events around the ethanol industry. An exploratory visit to the newspaper archives in Sao Paulo, Brazil, in July 2008 confirmed the availability and access to the newspaper's articles published since 1975. The material is indexed by subject. Electronic access is available from 1997. Therefore, the data ranging from 1975 through 1996 was performed through a manual search in the archives of the Brazilian newspaper.

Once the data for Brazil was limited to newspaper articles, U.S. sources were also limited to newspaper articles for consistency and to avoid sample bias. The database Lexis-Nexis Academic was used to search the New York Times and Washington Post, the two American newspapers covering most news on biofuels since early 1970s. The search was limited to the period between 1975 and 2008. The Brazilian source O Estado de Sao Paulo was not available in the database LexisNexis. The search into the newspaper was done in the archives, at the newspaper's headquarters in Sao Paulo, Brazil, during the summer of 2009. The search was manual between the years 1975 and 1996. I used an internal database to search the period between 1997 and 2008. Both manual and database searches followed the same keyword pattern used for the American sources. The keyword strategy is described in the methodology.

All articles gathered from the Lexis-Nexis database were downloaded into text compatible software. Each individual article was saved as an individual file. The same process was done for the electronic articles downloaded from the Brazilian newspaper. Articles from the physical archive were individually scanned and saved into individual files. Overall, the complete dataset is composed of 1,750 references or newspaper articles: 431 from the New York Times, 331 from the Washington Post, and 988 from the O Estado de Sao Paulo.

Newspaper articles are not a perfect representation of past events, since they are influenced by interpretation and relevance of the topic at the time of the publication. An important weakness of the data relates to the paucity of scientific or technical information about the technology. Since it covers only events reported by the media, the data does not take into account scientific sources of information, only newspaper articles that may underreport research taking place in a technology field. The data underestimates events related to knowledge creation and knowledge diffusion in the two countries. Notwithstanding, the mixed aspect of the methodology addresses part of this problem by having qualitative and quantitative methods complementing each other. In this study, the narrative tries to complement some of the information left out by the quantitative analysis, providing a clear picture of the innovation trajectory of ethanol in the U.S. and in Brazil since 1975.

4.3 Coding

The research design is based on the assumption that each newspaper article represents an empirical observation of an event, also the object of analysis for the purpose of research. Events reported in multiple stories are treated as "double", and were not counted in the quantitative analysis. Each newspaper article was imported into a master NVivo file. Each newspaper article or source was coded using the tools of NVivo software according to the year it was published (1975 through 2008), country it is reporting about (U.S. or Brazil), and functions of innovation they were assigned to. The coding process followed a codebook that was designed based on previous research, and enhanced to maximize intercoder reliability. All references from the New York Times were coded into more detailed categories subordinated to the main codes, or the 8 function of innovation. More than 100 sub-categories were freely created, some of them more general, others more specific. At the end of the process, these sub-categories were analyzed, and many of them were merged to eliminate redundancy. NVivo offers many advantages for inductive coding, because it allows the analyst to go back and forth to the coding and to the original source that originated it. NVivo also allows the migration of subcategories from one main coding or function to the other. This flexibility maximizes reliability. The codebook (Appendix A) was shared with a second coder who was trained to code a small sample (34) of the dataset. The 34 references were drawn from the newspaper Washington Post, chosen numerically and distributed from early to late years. Both coders converged on 25 out of 34 articles. From the 9 references on which they diverged, they were able to agree on 6 after some clarification. The coding of the remaining 3 references diverged because of subjectivity. The subjectivity was addressed by clarifying assumptions and better describing the functions of innovation in the codebook.

4.4 The Methodology

The methodology is based on process analysis[29] (Poole et al., 2000) of chronological events observed in two case studies – the development of ethanol in the U.S. and in Brazil. The methodology has been applied and tested in a previous dissertation thesis investigating innovation systems of biomass energy in Germany and in the Netherlands (Negro, 2007). Taking historical events as unit of analysis emphasizes temporal development, and facilitates determining how the process of innovation, development and change unfolds over time. One critical assumption is path dependence, or the mechanism under which an event can be explained based on the history of preceding events (Poole et al., 2000).

In process research, the goal is to create a chronological list of events around a specific technology, code the events in categories defined by the theory, and identify the processes or the patterns that explain how innovation occurs. The following procedure was applied into two case studies looking at the evolution of ethanol as biofuel during the last thirty years, in the U.S. and in Brazil.

1) Bibliographic research: a search was performed in the database LexisNexis Academic looking for references reporting events related to developments of ethanol and its application as a biofuel. As has been explained earlier in this chapter, the search was

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[29] This specific method was developed by a group of scholars within the scope of the Minnesota Innovation Research Program (Poole et al. 2000 Eds; Poole et al. 2000 in Van de Ven et al. Eds.).

limited to the American newspapers the New York Times and the Washington Post. The following search strategy was used:

> *(ethanol OR bioethanol OR gasohol OR sugarcane) AND INDEX-CODE((ALTERNATIVE FUEL PROGRAMS OR BIOFUELS AND AUTOMOTIVE) AND (BRAZIL OR UNITED STATES))*[30] *AND DATE(>=1975-01-01 and <=2008-12-31)*

For the physical archives in Brazil, I followed instructions given by the director of archives, after briefing him about my research focus. Following the archives' indexation criteria, I searched in the files named "Proalcool" (the Alcohol Plan of 1975), "alcool para motor" (alcohol for engines), and "carro a alcool" (car running on alcohol). The articles that covered accidents, criminal investigations, were not included. I was authorized to make copies of all articles of interest.

2) Coding of events: The coding process is qualitative in nature. Independently of what they represent, events are always coded with weight 1, either positive or negative. For example, an event relating to investments in R&D results in one positive unit (+1) allocated to the function knowledge creation in the specific year. Conversely, events can also allocate negative unit values (-1) to the functions they represent. For example, an event relating to a plant that shuts down leads to the allocation of a negative unit value (-1) into the function entrepreneurship. Events that relate to events that are external to the system, or exogenous, such as price changes in oil, gasoline, economic policies that relate to ethanol, but are not endogenous to the innovation process are classified as context. As previously mentioned, the codebook (Appendix I) was generated by using NVivo software. Once the coding of all sources was done, the results were transferred to an Excel worksheet for quantitative analysis.

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[30] INDEX-CODE refers to vocabulary controlled by the database.

3) Data analysis and plotting: events were plotted by category of function and by country against time.

4) Interviews with specialists: This step gathered information obtained from unstructured interviews with specialists from the U.S. and from Brazil. The goal of the interviews was to complement the data from newspapers and gray literature with insights from specialists who have experienced many years of the innovation process of ethanol. Because each specialist had a different focus, the interviews were geared towards the experience of each interviewee.

5) Process analysis: this step used the chronological sequence of events (coded by functions of innovation) to develop a narrative storyline. The goal was to identify positive (virtuous cycles) and negative (vicious cycles) paths that may have promoted or hampered the innovation process of ethanol. This step took into account the different contexts of each country, and the exogenous factors influencing the development of innovation over time. The goal was to explain how functions interact to each other leading to positive and to negative feedback mechanisms. By linking narrative to graphic representation of functions, this step identified the causal patterns that lead to the emergence of positive or negative cycles of change and development. This step also added information not included in the previous steps. It took into account grey literature, books, and interviews with specialists. The functions were plotted all together by periods of time to illustrate how the unfolding of events contributed or not to the building up of functions of innovation over time.

6) Comparative analysis: the steps described were applied to both countries, providing the necessary data to compare the patterns of development of innovation in ethanol over time.

CHAPTER 5

DATA ANALYSIS

5.1 The functions

Approximately one fourth of newspaper articles (470) were coded as contextual or reported events considered exogenous to the process of innovation, and not fulfilling the eight functions of innovation. Some examples included articles reporting change in price of ethanol or corn price, or international trade issues, China or India's food consumption, political issues over the Farm Bill, or the presidential campaign and the Iowa Caucus. Table 4 shows the list of functions, with the number of events assigned to each function, differentiating by whether it contributes to the process of innovation (positive sign), or is detrimental to it (negative sign). For the codebook, please see Appendix I.

Table 4: Ethanol in the U.S. and in Brazil: coding of events (functions of innovation)

Functions of Innovation		**+**	**-**	**Total**
F1	Entrepreneurship	92	17	109
F2	Knowledge Creation	124		124
F3	Knowledge Diffusion	35		35
F4	Guidance of Research	192	165	357
F5	Market Formation	101	9	110
F6	Resource Mobilization	93	7	100
F7	Legitimation	113	43	156
F8	Building of Capabilities in the Downstream Market	190	71	261
Context				470
Double				30
Total				1750

The data shows that among the articles which events were endogenous or were embedded within the process of innovation, most of them were coded as Guidance of Research (F4) and Capability Building in the Downstream Market (F8).

Table 5: Ethanol in the U.S. and in Brazil: coding of events (functions of innovation)

Functions of Innovation		**US +**	**US -**	**BR +**	**BR -**
F1	Entrepreneurship	43	11	49	6
F2	Knowledge Creation	42		82	
F3	Knowledge Diffusion	3		32	
F4	Guidance of Research	58	80	134	83
F5	Market Formation	52	8	49	1
F6	Resource Mobilization	31	5	62	2
F7	Legitimation	73	27	41	16
F8	Building of Capabilities in the Downstream Market	34	21	156	50
Context		254		217	

There are only 35 articles reporting events coded as knowledge diffusion for both countries together during the whole period. This function of innovation was operationalized as events related to conferences, meetings, workshops around the theme of ethanol. Since this research used mostly newspaper articles to code functions of innovation, it is expected that events such as meetings and conferences happening around the technology may have been underreported.

When analyzing by country (table 5), results show that the most relevant function in the U.S. was Legitimation (F7), while the most prevalent function in Brazil was Building of capabilities in the Downstream Market (F8). Conversely, the function holding the most negative effort, or most counteracting the process of innovation in the U.S. was Guidance of Research (-F4). During the last years, many reports were published alerting about the harming effects of growing production of corn ethanol. Reports presented models suggesting that the production and use of corn ethanol generated more GHG emissions than gasoline (OECD, 2008), and that the growing use of corn for fuels could cause long term impact to food commodity prices (Baffes & Haniotis, 2010). These negative reports changed some policy targets, and generated a negative expectation about the future of corn ethanol as a biofuel. The same was true for Brazil, but the negative effects into sugarcane ethanol were less intense because the product was already consolidated in the Brazilian domestic market. These results in isolation are limited without a thorough analysis of how the functions of innovation evolved over time. This analysis is presented in the following chapters of this dissertation.

5.2 Number of events over time

Making a comparison by country over time, Brazil emerges as a player earlier than the U.S. Because of the national impact of the Brazilian ethanol in the 1970s, the number of events in Brazil was higher than the number of events in the U.S. during that time. The first ethanol activities in the U.S. were more concentrated in the Corn Belt region, and did not have the national impact of the Brazilian events with the announcement of a government-led national plan for the production of ethanol to replace gasoline in the long term (fig. 12).

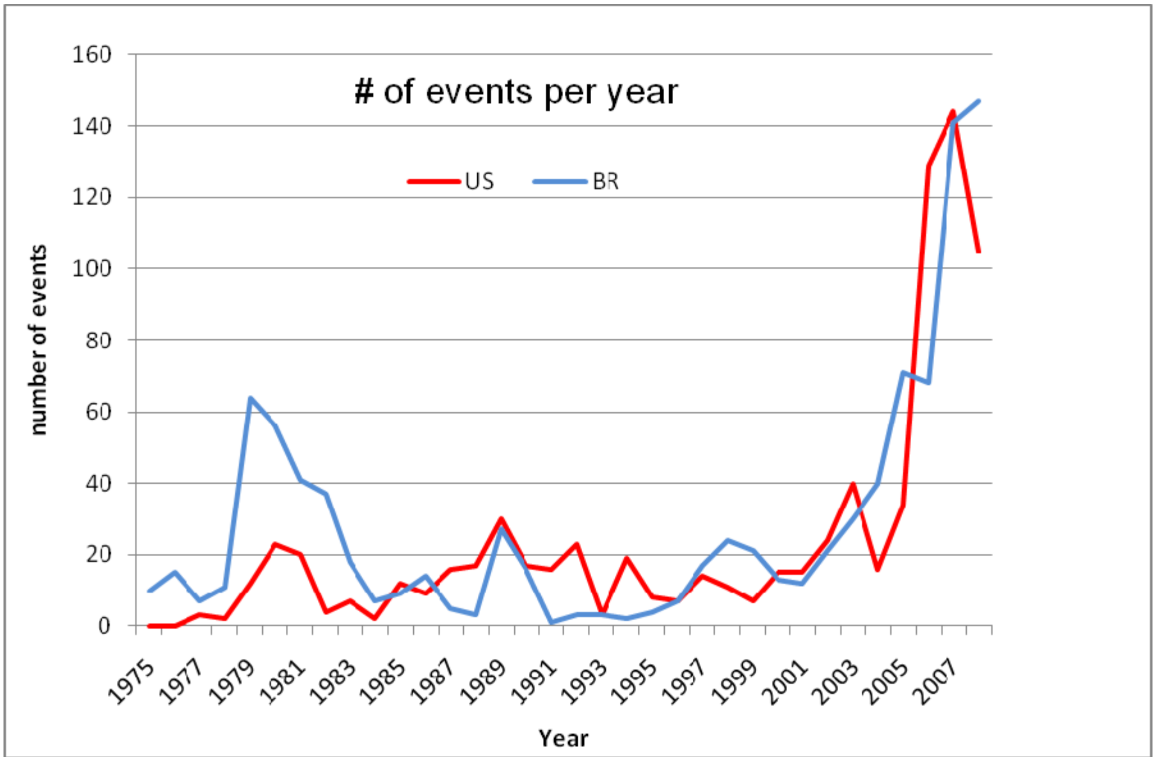


Figure12: Brazil and U.S. - number of events reporting on ethanol (including context)

Ethanol became a more prominent issue after the year 2000. The number of events reported between 2000 and 2008 (9 years) is approximately twice as many as the number of events reported between 1975 and 1990 (16 years). And despite Brazil's dominance in the early period, the issue of ethanol in the U.S. becomes also evident during the last eight years of the analysis (fig. 13, and 14).

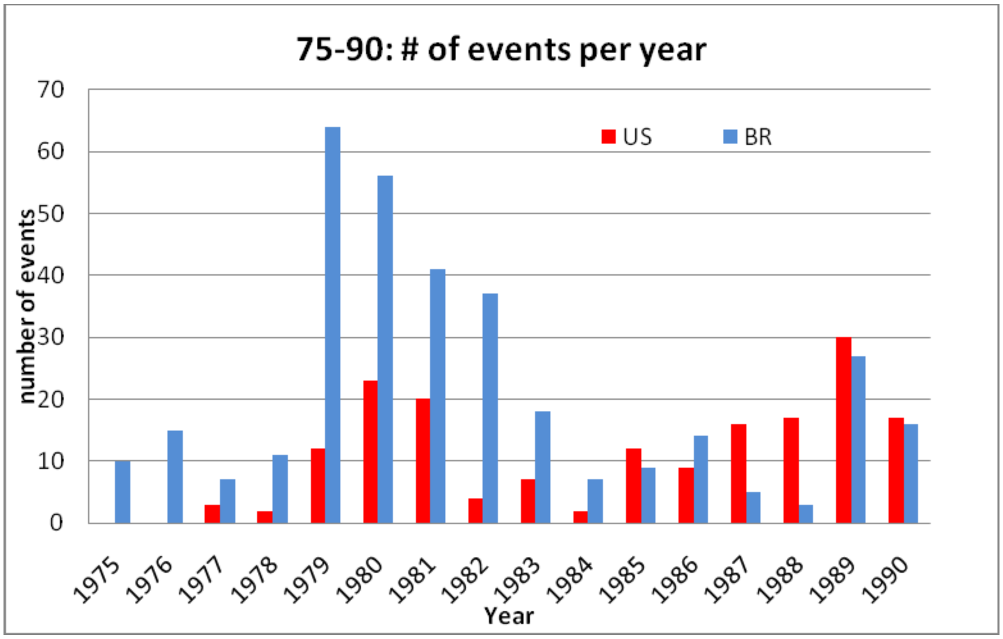


Figure13: Brazil and U.S. - number of events reporting on ethanol (1975 - 1990)

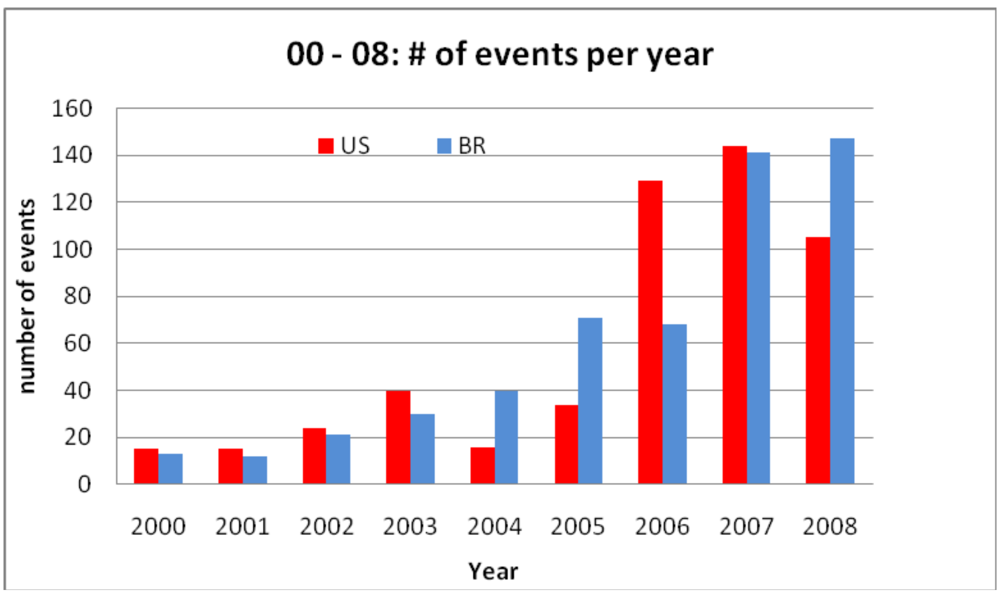


Figure 14: Brazil and U.S. - number of events reporting on ethanol (2000 - 2008)

As mentioned in the methodology, the coding process is qualitative. Events are coded with the same value - positive 1 or negative 1. In other words, events are coded with the same weight regardless of their importance or relevance for the innovation process. Therefore, the quantitative data here presented in tables and graphs cannot be considered in isolation without a thorough understanding of how the sequence of events unfolds. The narratives for each country describe the events and highlight the significance of time and history to explain how the dynamics of innovation of ethanol unfolds for each country. The next chapters explore those in detail.

CHAPTER 6

NARRATIVE ETHANOL UNITED STATES

This chapter reveals how the dynamics of innovation of ethanol unfolds during the innovation process. It uses a narrative approach to describe the trajectory of the innovation of ethanol in the U.S. between 1975 and 2008. The narrative is built from the chronological compilation of articles from the New York Times and the Washington Post that compose the dataset of this research. Articles from the Brazilian newspaper O Estado de Sao Paulo reporting events specific to ethanol in the U.S. are also included in the narrative. The articles were often complemented by gray literature. The unfolding of reports of events is divided in the chapter in four different segments of time:

1) The Arab Oil Embargo and the gasohol boom (1975-1980)
2) The Reagan era and cheap oil – the end of gasohol boom (1981-1990)
3) The Clean Air Act: an opportunity for ethanol as oxygenate (1991-2000)
4) The new millennium: energy security, climate change. Reaching to advanced ethanol (2000-2008)

Each session starts with a brief summary, and ends with a brief analysis of how the unfolding of events relate to the functions of innovation (in bold). The analysis is complemented by a graph that illustrates the cumulative evolution of each function during the period.

Henry Ford's aspiration for vehicles to be operated with agricultural-based fuel did have a strong beginning in the US where ethanol was commonly produced and used into the 1920s and 1930s. During that time, several of the biofuel concepts that are being pursued today, were also promoted. Ford's Model T was considered the first flex-fuel vehicle and could be modified to operate on either gasoline or pure alcohol. A variation of today's ethanol, except with a 25% alcohol blended gasoline, was marketed by Standard Oil in the Baltimore area during the 1920s. Ethanol plants also existed in the Midwest. In 1938, an ethanol plant located in Atchison, Kansas, produced 18 million gallons of ethanol a year and supplied more than 2000 service stations in the Midwest. Unfortunately, all of this progress came to a sudden halt in the 1940s when large volumes of inexpensive petroleum and natural gas became available. (US DOE, 2000).

Although WWII spurred some increase in the consumption of ethanol, most demand was still for non fuel use. The interest for renewable fuels was revitalized in the 1970s as a result of the Arab Oil Embargo, and the fall of the shah of Iran (Bettelheim, 2006). The phasing out of lead as an octane enhancer by the late 1970s sparked some interest on the use of ethanol as a fuel additive.

6.1 Arab Oil Embargo and the gasohol boom (1975-1980)

The first period of the ethanol innovation history marks the beginning of the industrial commercialization of ethanol (entrepreneurial activity-F1, and resource mobilization-F6)), which was accelerated by three exogenous factors: 1) the oil crisis of 1973 and 1979; 2) the oil price volatility; and 3) the oversupply of grains in the market. The National Energy Act of 1978 benefits gasohol producers with tax credits, helping gasohol to compete with gasoline 100% (market formation -F5) in the Midwest. The regional boom of gasohol in the Midwest has the support of local farmers and politicians, who advocate for national policy that benefits the burgeoning local gasohol industry (legitimation-F7). The gasohol industry also takes advantage of renewable energy programs funded by the Carter administration (knowledge creation-F2; resource mobilization-F6).

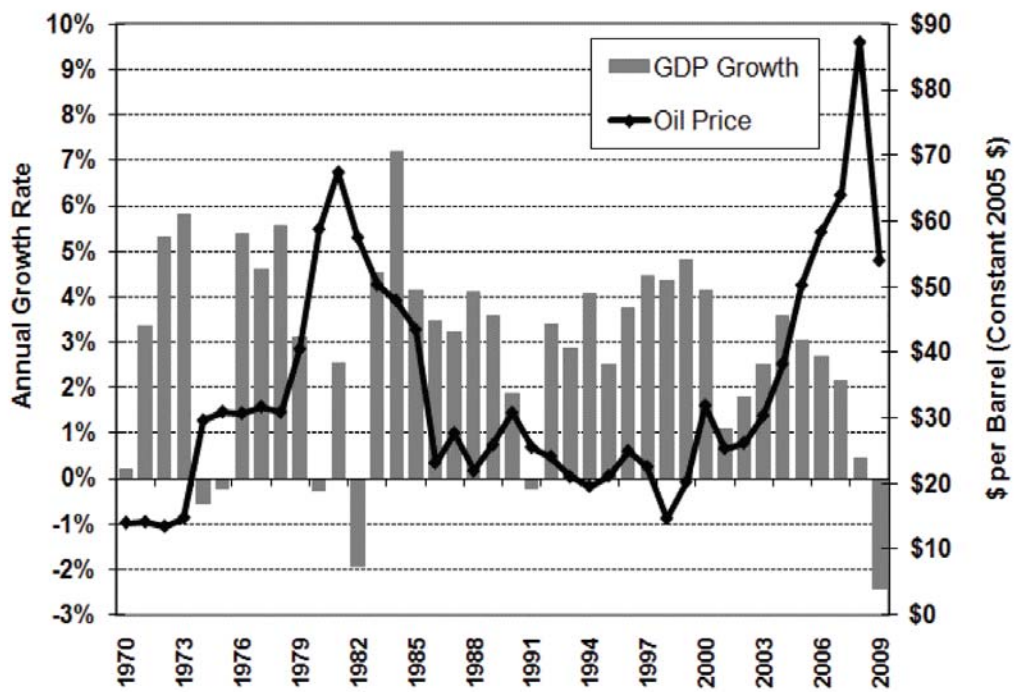
Entrepreneurship (F1) in the ethanol industry addressed the anxiety of farmers looking for additional markets for large production of corn. The commercial boom of the ethanol fuel industry during the 1970s came as a relief for farmers during a period of crop surplus and low grain prices. To create an additional application for corn, struggling American farmers began to install small distilleries to produce ethanol. They used their corn processing plants to process surplus grains, developing a small market for biofuel ethanol. The Arab Oil Embargo gave a significant incentive to the burgeoning industry, in a moment when America realized the vulnerability of its energy supply for the transportation sector.

The Arab Oil Embargo helped justify national policy promoting the production of renewable energy, and increasing expectations about the future of ethanol as a replacement or complement of gasoline (guidance of research F4). The images of long lines in gas stations symbolized the U.S. reliance on foreign oil, and the serious implications of another oil embargo to the American economy. The Energy Policy and Conservation Act of 1975 was a response of Congress and President Fords' administration to the oil embargo, and set the tone for a set of policies for energy conservation at the national level. One important item included the doubling of efficiency standards for new vehicles by 1985 (Hakes, 2008).

Higher oil prices (fig.15) helped the economics of the ethanol business. Between 1970 and 1981, oil prices increased from $3 dollars a barrel to $35 dollars a barrel (EIA, 2002). Ethanol sprawled in the Midwestern states, where developed the core of the corn business in the country. Ethanol fuel was sold as gasohol, a mixture of 10% ethanol and 90% gasoline.

Major oil price shocks have disrupted world energy markets five times in the past 30 years (1973-74, 1979-80, 1990-91, 1999-2000, 2008). Most of the oil price shocks were followed by an economic recession in the United States.

Figure 1.4. Oil Price and Economic Growth, 1970–2009



Source:
Greene, D.L. and N. I. Tishchishyna, *Costs of Oil Dependence: A 2000 Update*, Oak Ridge National Laboratory, ORNL/TM-2000/152, Oak Ridge, TN, 2000, and data updates, 2010. (Additional resources: www-cta.ornl.gov/publications)

Figure 15: Oil prices and GDP growth – 1970 – 2009. Transportation Energy Data Book. Edition 29, Oak Ridge National Laboratory - cta.ornl.gov/data

The emergence of ethanol during the 1970s did not come without controversies and resistance from the oil industry. In the mid 1970s, tests had shown that gasohol decreased tail pipe emissions of hydrocarbons and carbon monoxide, but increased emissions of nitrogen oxide, one of the precursors of greenhouse emissions. A Clean Air Act amendment in 1977 had banned the use of gasohol, because tests did not prove its environmental safety. In 1978[31] the Environmental Protection Agency (EPA) decided to allow production and commercialization of gasohol in the Midwest of the country, because the region represented a very small portion of the gasoline market. The American Petroleum Institute condemned the development of the gasohol market, and issued a report containing a negative evaluation of alcohol for automobiles.

Considering ethanol a renewable energy and a source of rural development in the Midwest, many politicians advocated for ethanol publicly (legitimation F7). Ethanol produced in the U.S. was promoted by politicians in the Midwest as one of the alternatives to decrease the U.S. dependence on foreign oil. The U.S. Congress soon after approved legislation to fund ethanol research, finance loans to ethanol producers, and reduce federal tax on the production and commercialization of ethanol fuel. In 1978, Congress passed the National Energy Act, giving a tax credit of 4 cents for each gallon of gasohol, a mixture of 10% ethanol and 90% gasoline. The incentive was equivalent to 40 cents of tax benefits for every gallon of ethanol mixed into gasoline. Ethanol fuel offered an economic opportunity for corn growers in the Middle West, in special in Iowa, Nebraska, Illinois, Minnesota, and South Dakota. Ethanol became a profitable market in the region.

The fall of the Shah of Iran in 1979, and the second energy crisis in America gave voice to an already influential ethanol lobby in Washington DC, speeding up the pace of development on the business. In the Midwest, there were almost 500 gas stations selling the alternative fuel as gasohol. Archer Daniels Midland Inc, known as ADM was the largest producer of ethanol in the U.S. The company began production of ethanol in 1977, after transforming and adapting its vodka and gin manufacturing plants for ethanol

[31] "Motor vehicles are a major source of urban smog," EPA Deputy Administrator Barbara Blum pointed out. "We must improve the use of cars, trucks and buses, and plan and manage our urban transportation systems more efficiently in order to reduce air pollution." From http://www.epa.gov/history/topics/trans/02.htm.

production. In 1979, it accounted for 80% of ethanol production nationwide (Bernton et al., 2010). Over time, ADM became the largest corporate donor to politicians and law makers, and was considered by many an example of corporate welfare in the ethanol business for many years.

Ethanol enjoyed large investments from the federal government (resource mobilization F6). Despite strong support from Midwestern state politicians and financial help from federal government incentives, gasohol had only 2% of the gasoline market in 1980. Notwithstanding, players in the industry kept investing in technology. Some examples included the National Distillers and the Chemical Corporation announcing plans for a new ethanol plant, using a continuous fermentation process, which reduced significantly the production cost associated with the conventional process. Investments in technology and research were not limited to the private sector. The federal government was also committed to investing in alternative fuels. The Department of Energy created the Office of Alcohol Fuels to accelerate research and development of ethanol and methanol. Although there was R&D capability and knowledge acquired on cellulosic ethanol, the sense of urgency on the energy independency problem led the administration to focus research efforts on short term promising technologies, such as corn ethanol (Wyman, 2001). In 1980, the US government established the US Synthetic Fuels Corporation, a public-private partnership for the development of synthetic fuels from coal, ethanol, and power production from biomass.

Gasohol was becoming popular in the country. With prices slightly higher than unleaded gasoline, gasohol attracted consumers for its positive appeal associated with energy security and driving performance (guidance of research F4). Gasohol accounted for 13% of Texaco sales in the Washington region. Texaco had 1,400 stations offering gasohol around the country. Other oil companies, such as Amoco offered gasohol mainly in the grain producer states of the Midwest. Exxon did not market gasohol, because it believed the production of ethanol used more energy than the energy contained in the fuel.

For President Carter, the energy dependency problem was considered the "moral equivalent to war". Carrying a sense of urgency, his administration main goal was to replace oil imports with synthetic fuels produced in the U.S. Under the Carter administration there were programs and investments promoting renewable fuels (guidance of research F4; knowledge creation F2; resource mobilization F6). The most important programs of the Carter administration focused on the production of synfuel[32] from coal, and alcohols such as methanol and ethanol. The Energy Security Act funded $1.27 billion in federal loans for biomass fuels and loan guarantees for coal and shale-based synthetic fuels. During the 1980s, some oil companies, especially those having stakes in the coal business, began investing in plants producing methanol using the coal liquefaction process. However, ethanol became the fuel of choice for the market of oxygenates for gasoline. Methanol was considered very toxic and less suitable for the production of gasohol than ethanol (Bernton et al., 2010).

Translating the dynamics of innovation to the functions of innovations:

Exogenous factors increased positive expectations for gasohol (research guidance-F4), leading policy makers to regulate and provide tax incentives (National Energy Act 1978) for the production of gasohol in the Midwest (entrepreneurship-F1; market formation-F5). Moreover, farmers and ethanol producers formed a group with common interests, who very early became powerful advocates for ethanol and gasohol production (legitimation-F7). These initiatives reinforced entrepreneurial activity (F1), knowledge development (F2), additional investments (resource mobilization-F6), and the optimism in relation to the future of the industry

[32] Synfuel or synthetic fuel can be obtained from coal liquefaction or natural gas reform.

(guidance of research-F4). The Carter Administration reinforced the positive climate for renewable energy, providing additional funding for research on ethanol (F6, F2). However, the emergence of gasohol and ethanol would soon slow down with the new Regan administration and cheap and abundant oil during the 1980s. The graph below illustrates the evolution of the functions of innovation during the first period of innovation of ethanol in the U.S. Most functions of innovations have a positive start during the period. Entrepreneurial activity (F1) was reinforced by the positive expectations of the industry (guidance of research-F4) and by tax incentives implemented in the region (market formation-F5).

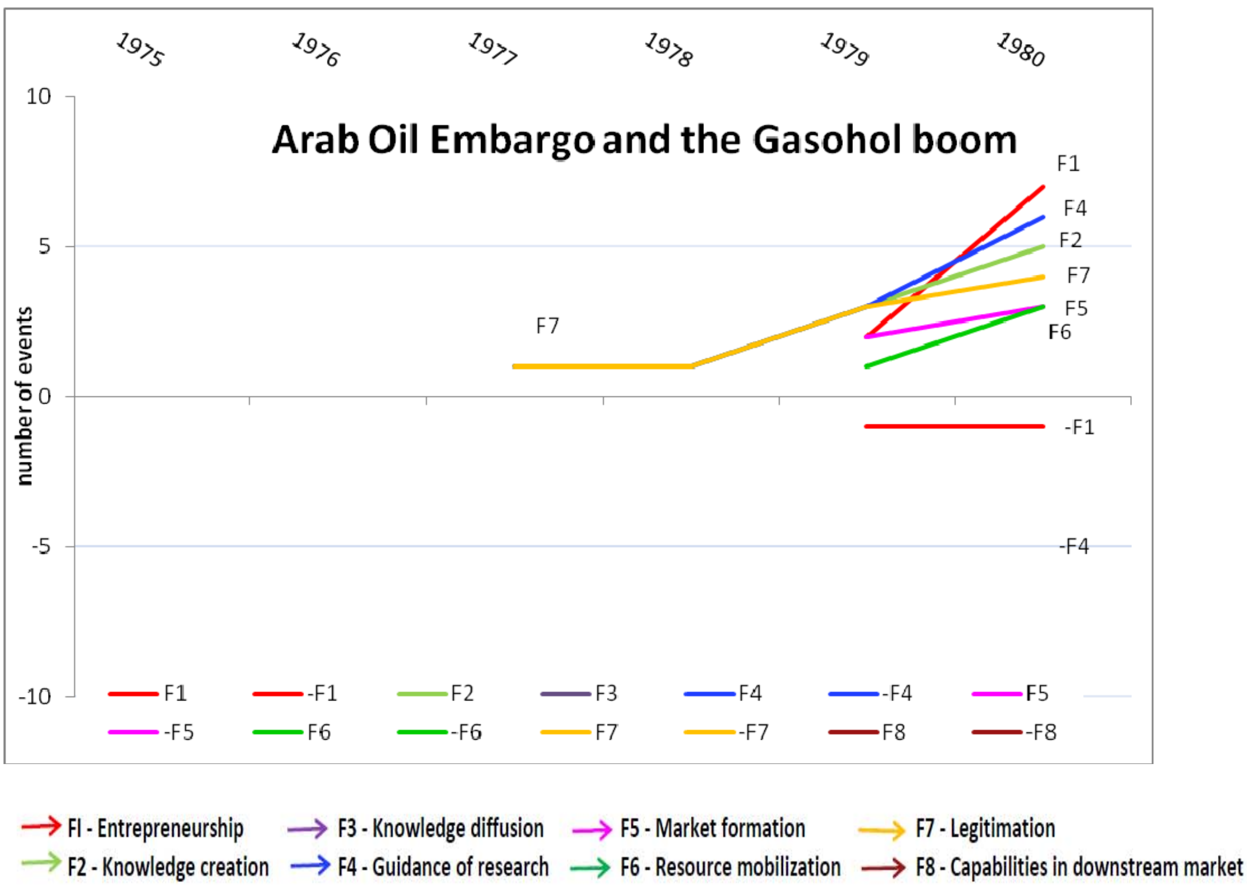


Figure 16: Gasohol Boom - Map of functions of innovation 1975-1980. Source: New York Times and Washington Post

6.2 The Reagan Era and Cheap Oil - the end of the gasohol boom (1980-1990)

The 1980s marked the end of strong government incentives for renewable energy, and the stabilization of international oil prices. Ethanol programs lost government funding (resource mobilization -F6), and gasohol lost market and production to unleaded gasoline (entrepreneurial activity -F1). However, ethanol was already valued by its anti-knocking properties and as a potential replacement for lead in gasoline, creating a positive expectation about the potential market of ethanol as an additive (guidance of research F4). Some local initiatives in California began testing cars with engines running on 100% methanol (downstream market F8; knowledge creation), but those initiatives did not have a significant impact.

In 1981, funding for research decreased significantly (resource mobilization - F6), and shifted to more long term and high risk projects, those that would not have been pursued by the private sector. R&D efforts were limited to ethanol produced from biomass, using the enzymatic process (Wyman, 2001).

The Reagan Administration planned to end the large loan program to the ethanol industry created by the Carter administration. To counter this movement, a coalition of gasohol interests created the Renewable Fuels Association (RFA). The RFA transformed itself in a powerful lobbying organization, and continually advocated for ethanol interests in the Congress. These actions strengthened the legitimation of ethanol at that time (legitimation F7). But the Reagan administration's large federal support program in the form of loan guarantees went to the production of synthetic fuels from coal, shale, and tar sands (Bernton et al., 2010).

By 1981, oil supply had normalized, and prices were stable. The consumer did not see much advantage in using gasohol. Following low interest from consumers, Texaco decided to stop sales of gasohol in many of its gas stations. The company stopped sales in the Northeast states, and replaced gasohol with premium grade unleaded gasoline. ADM, the largest producer of ethanol decided to delay one of its large investment plans in ethanol.

During the early 1980s, the Reagan administration ended the Carter's era of strong funding for alternative fuels. Investments to promote ethanol innovation decreased (resource mobilization -F6). Funding for ethanol was cut drastically, along with electric vehicles and methanol. However, amidst the economic recession and financial hurdles for farmers and land owners, some strong voices called for the support of fuels from agricultural crops, arguing that those programs could bring relief for economically distressed American farmers. Some environmentalist groups claimed that programs like those supporting ethanol from corn were in fact contributing to price increase in grains, inflating prices in the food market. But a report commissioned by Ford Motor Company and the Energy Department used computer models to show that the production of fuels from feedstock would not harm the production of food.

The state of California was promoting alcohol as a renewable fuel (research guidance F4). The state of California and Ford Motor Company supported the use of methanol as an alcohol fuel. In 1981, Ford had delivered 40 methanol cars to California, LA County. The county installed several methanol pumps, and in 1983 Ford began market tests with its new car using methanol[33] . More than 500 cars were delivered to local fleets and to state officials. The test was followed by the California Energy Commission. The methanol was blended with 10% gasoline to help start the engine at low temperatures. Despite the small number of cars being tested, users reported minor problems, with an overall positive performance. Although methanol has energy content 50% lower than gasoline, methanol provides a better performance, as long as engines are

[33] Methanol was produced from indirect liquefaction of coal, or from natural gas. Methanol may also be produced from biomass sources. As ethanol, methanol is compatible with flex fuel vehicles.

adapted to maximize performance with the alternative fuel. Methanol and ethanol had long been used in motor race because both fuels have a higher energy density than gasoline, deliver more power, more torque, as a result of their anti-knocking properties.

The phasing out of lead from gasoline since the Clean Air Act of 1970 opened a potential market for ethanol, thanks to its anti-knocking properties. This increased the expectations of a potential market for ethanol as a replacement for lead in gasoline (guidance of research F4). The Environmental Protection Agency determined that the level of lead in gasoline should be reduced to 0.1 gram until January 1st 1986[34] . The amount of lead in gasoline in 1975 was between 2 and 3 percent. The complete banning of leaded gasoline did not come until 1996. Companies like American Fuels Technology, Inc., found a market opportunity with the new EPA ruling, because ethanol was considered not only a fuel extender, but also a fuel enhancer because of its anti-knocking properties.

In 1987, California decided to go forward with its plans to use methanol as a fuel to reduce its pollution problems. The state had made an agreement with Arco (Atlantic Richfield Corporation) for the commercialization of methanol in the state in 70 gas stations. At the same time, the system made the first efforts to develop capabilities in the downstream market (F8). On the transportation side, Ford had developed cars capable of running with methanol or gasoline. California officials hoped to replace 30% of the state's gasoline consumption with methanol by the year 2000. Methanol was also making strides in other states. New York was experimenting buses running on methanol. The Reagan administration also supported the development of ethanol and methanol programs to replace part of the gasoline in the U.S. The government planned to recommend these alternative fuels with economic incentives, because of their potential to curb emissions in

[34] http://www.epa.gov/history/topics/lead/02.htm

the transportation sector. The EPA would provide guidance to the states in how to use the alternative fuels to comply with the Clean Air Act requirements.

By the end of the 1980s, the environmental appeal of alcohol fuels revived the interest for alternative fuels, after a decade of low oil prices ended the growing cycle of ethanol and methanol during the 1970s. The competition with oil prices forced many industries to shut their ethanol and methanol plants. A government report estimated that approximately half of the 165 alcohol plants operating during the early 1980s were still operating in 1987. The strong entrepreneurial activity of the previous period was counteracted by low oil prices (-F1) and lack of incentives from the government (-F4). However, the environmental appeal of ethanol as a renewable source helped to revive the interest for ethanol in the late 1980s, increasing positive expectations about the technology (guidance of research F4). The prospects of a new market for alcohol fuels, and the support of politicians revived the interest for the programs. The government announced that the sales of gasohol in 1986 had reached approximately 8% of gasoline sales, against 2% during the early 1980s.

In April of 1988, the Senate approved legislation that gave incentives for the production of alternative fuels vehicles (guidance of research F4). The measure would help automakers meet the efficiency requirements for corporate average fuel economy (CAFE standards) for cars and light trucks. The bill was approved by the House and became law. Automakers were entitled to produce cars with engines designed to run on ethanol, methanol, or natural gas. The main process to produce methanol used natural gas, raising questions about methanol's benefits for energy independence in the long term. Oil companies were not supportive of methanol as an alternative fuel. Addressing the criticism, the EPA issued a report highlighting methanol's environmental benefits, and arguing that the alternative fuel would be competitive with gasoline at the pump.

In 1989, President H.W. Bush announced a plan to curb pollution in large cities by increasing the use of ethanol, methanol, and natural gas. The plan required annual sales of one million alternative vehicles in the most polluted cities until 1997. The plan, however, did not have the support of automakers, who claimed that alternative fuel vehicles were an expensive option for consumers. Pressured by tough environmental regulations, automakers and oil companies announced a joint research program to develop vehicle and fuel technologies to decrease levels of pollution and to decrease the emission of greenhouse gas emissions. The research plan contemplated research on reformulated gasoline, and alcohols. The Bush plan of a “National Energy Strategy” focused on energy conservation, and renewable energy such as ethanol and solar energy (guidance of research F4). In addition, there was a stronger legitimation towards ethanol at that time.

The ethanol lobby was very strong. Ethanol enjoyed a federal tax credit of 60 cents a gallon, helping to cover the wholesale price difference between ethanol and gasoline. Since 1980, gasohol producers had received $4.6 billion in federal and state tax exemptions. Critics to subsidies argued that the tax incentives were nothing but corporate welfare, because the largest beneficiary of the tax credit had been ADM, which accounted for 75 percent of the production of ethanol in the country. The federal tax credit would expire in 1992, but a powerful lobby in Washington DC was fighting for the survival of the tax incentives for the ethanol industry. Besides large corporations like ADM, professional associations such as the National Corn Growers Association, the American Farm Bureau Federation, and the American Agriculture Movement all supported the ethanol industry in Congress.

Translating the dynamics of innovation to the functions of innovations:

During the 1980s, cheap oil prices reduced investments in R&D (resource mobilization- -F6) in ethanol and entrepreneurial activity slowed down (-F1). But with the banning of lead by the EPA in the 1970s, ethanol was already recognized by its anti-knocking properties (guidance of research-F4). The Renewable Fuels Association became the strong lobbying organization for ethanol in Washington DC

(legitimation F7). California adopted anti-pollution standards (market formation F5), and began tests with methanol and cars running on 100% methanol (knowledge creation F2) and (building capabilities in the downstream market F8). Some cities began tests with methanol to curb pollution problems (knowledge creation F2). The graph below shows that there is some building in the function guidance of research (F4), because of the expectation that ethanol could serve the market of oxygenates. There is some building of function legitimation (F7) with stronger lobbying for ethanol. Funding for methanol drove some activity of knowledge creation for testing cars running on alcohol (F2). However, none of those activities were strong enough to spur entrepreneurial activity. The graph does not show a sustained building of functions of innovation in the positive direction, suggesting the TIS ethanol was emerging but still lacking important activity to take off.

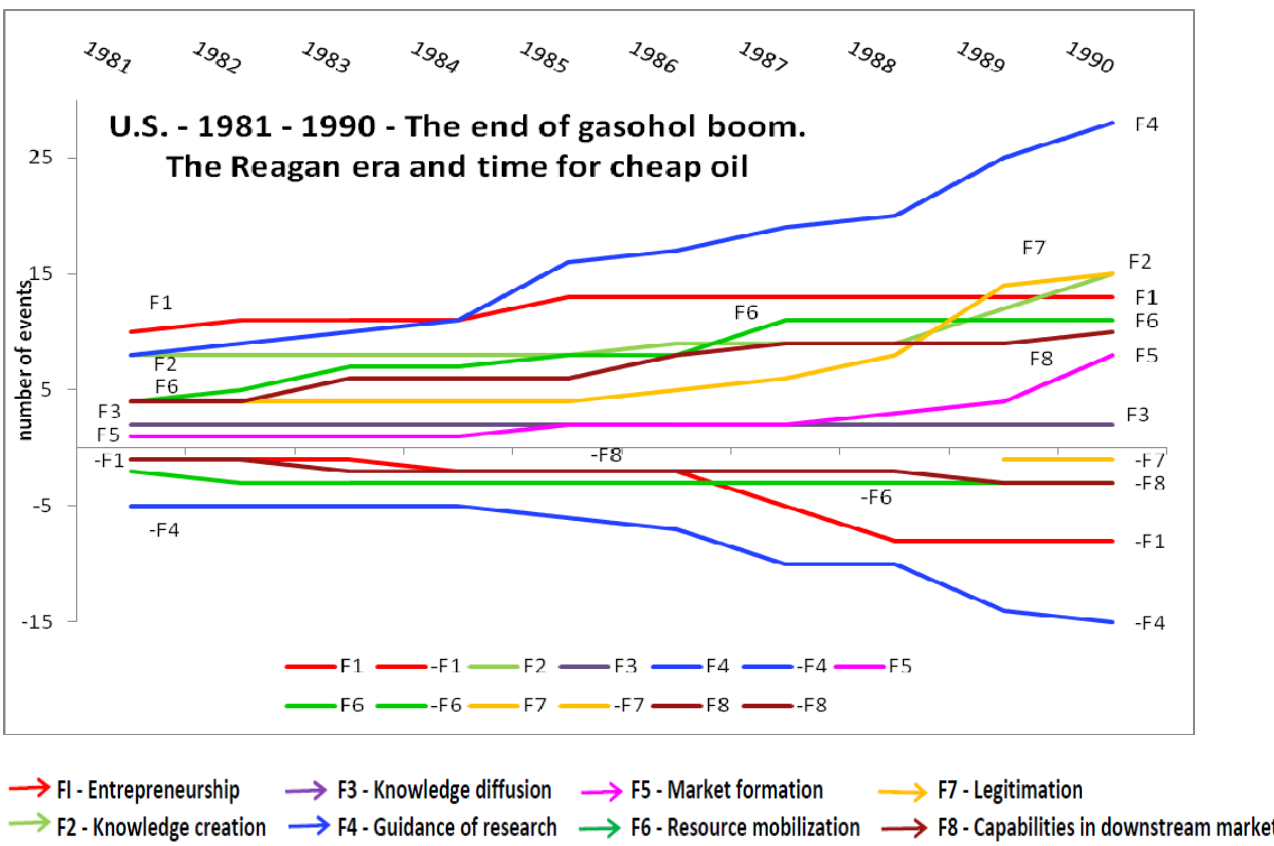


Figure 17: The end of the gasohol boom. Map of the functions of innovation. 1981-1990
Sources: NYT and Washinton Post

6.3 The Clean Air Act: an opportunity for ethanol as oxygenate (1990-2000)

The end of the last period was marked by a focus on methanol from coal. California and Ford tested some cars running on 100% methanol, and some states adopted blends of gasoline and methanol. Many ethanol plants shut down for lack of government support and market demand (entrepreneurial activity –F1). Although ethanol was considered a nice oxygenate for gasoline in more polluted areas (guidance of research F4), the product was deemed to increase smog levels during the warmer months in the most polluted cities (guidance of research -F4). The banning of MTBE in the late 1990s generated the necessary market demand to spur production of ethanol in the new millennium. Despite automakers' efforts to launch flex fuel vehicles (downstream market F8), most of them ran on 100% gasoline (downstream market -F8).

The Clean Air Act Amendments of 1990 required the nine most polluted areas in the country to sell reformulated gasoline mixed with additives like ethanol or MTBE (Methyl Tertiary Butyl Ether) beginning in 1994. The oil industry opposed the measure. However, oil companies and car makers made efforts to reduce the levels of emissions of gasoline. Major oil companies and automakers decided to collaborate in a project to investigate emissions coming out of tail pipes from the combustion of gasoline. The goal was to identify which components contributed the most to smog formation, and to change the formulation of gasoline to eliminate the most toxic emissions. Local governments in large cities were proactive in adopting measures to improve levels of emissions from transportation. Following environmental concerns, some large cities mandated the use of alternative fuels vhehicles, creating a potential market niche for ethanol (market formation F5). New York City and Los Angeles adopted alternative fuels vehicles in government fleets, using methanol, ethanol, and natural gas as alternative fuels.

In 1991, Volvo North America began testing flex fuel vehicles capable of running on methanol in California, strengthening capabilities in the downstream market of ethanol (F8). The technology included electrically heated catalytic converters so that cars would emit less toxic gases during cold months. In an effort to comply with the recently approved Clean Air Act amendment, Exxon planned to build three plants to produce MTBE, an oxygenate competing with ethanol. MTBE was cheaper than ethanol and easier to transport. Arco was a large MTBE supplier, and other oil companies had plans to increase consumption of MTBE.

At the local level, some states passed legislation promoting the use of alternative fuels vehicles, increasing the prospects for the use of ethanol as an alternative fuel (guidance of research F4). In California, the Air Resource Board adopted legislation to restrict emissions beginning in 1994. California and Texas laws pushed forward the use of automobiles compatible with alternative fuels like propane, natural gas, and alcohols like methanol and ethanol. In the meantime, the automobile and energy sectors joined forces to collaborate in research of alternative fuel vehicles (knowledge creation F2; knowledge diffusion F3). Detroit "Big Three" and Southern California Edison agreed to collaborate in research of alternative fuel vehicles. Electric vehicles were also included. Texas law required schools and government agencies to buy only alternative fuels vehicles beginning in 1991. The state also required the conversion of existing fleets to compatible alternative fuels vehicles until 1996. Despite incentives put forward by the state, the sales of alternative fuels in service stations were low, leading Chevron to stop installing methanol pumps throughout the state.

And more automakers joined forces building the capability of the downstream market of ethanol (F8). Following other American automakers, Chrysler also announced sales of flex fuel vehicles. The additional cost of the alternative fuel vehicles would be between $200 and $500 dollars. The production of these cars would give Chrysler a credit in corporate average fuel efficiency as determined by law. Different from other states, California offered buyers of AFV a subsidy of $2,000, pushing forward the commercialization of bi-fuel vehicles. However, those incentives did not guarantee that consumers would fuel their vehicles with alternative fuels, since the number of pumps offering alternative fuels was still very low.

In November 1992, the EPA began the Oxygenated Fuels Program as it was determined by the Clean Air Act of 1990. The new program required gas stations in 39 metropolitan areas of the country to sell gasoline blended with oxygenates like ethanol or MTBE. The goal was to reduce urban pollution, by decreasing the emission of carbon monoxide (CO) from tail pipes[35] . However, the EPA banned the use of ethanol in nine major cities (non-attainment areas) during the summer months, because the higher volatility levels of ethanol could make the smog worse. This came as bad news for the ethanol industry, bringing concerns that it would have negative impact for the development of the industry (guidance of research -F4). But advocates for the industry reacted immediately, trying to legitimize ethanol as an oxygenate appropriate to be consumed widely (legitimation F7). The corn lobby asked the EPA to waive the restriction, demanding that ethanol be sold year round nationwide. They were faced with tough criticism from the oil industry and environmental groups who argued that waiving the restriction would go against the Clean Air Act of 1990, which required a decrease in smog by 15% in nine major cities during the summer months, beginning in 1995. It was 1993, and time of reelection approached. Despite calls from the oil industry and environmental groups, President Bush answered the request from the corn industry, exempting ethanol from restrictions established by the Clean Air Act. The move increased sales of ethanol throughout the year.

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[35] http://www.epa.gov/history/topics/caa90/09.htm (07.06.2010)

In 1994, the Clinton Administration implemented policy mandating the use of ethanol as an alternative fuel (market formation F5). The federal government promoted the use of ethanol as oxygenate by mandating that 30% of additives to gasoline be produced from renewable sources. Corn ethanol was the only additive produced commercially that was considered a renewable fuel. The mandate was good news for corn and farm lobbies, but made oil companies angry with the prospects of ethanol taking a market share of their own gasoline oxygenate, MTBE, produced from methanol. Methanol was produced from natural gas or coal, two non-renewable sources of energy. The oil industry challenged the government order by going to the US Court of Appeals in the District of Columbia. Some months later, the Court recognized the legitimacy of oil companies' request, blocking the Clinton Administration from mandating the use of ethanol with gasoline.

In 1995, the reformulated gasoline (RFG) requirements were implemented in nine cities (the nine worst ozone nonattainment areas in the country). EPA estimates that until 2000, RFG would account for one third of the gasoline sold in the country. One of the RFG requirements was the use of oxygenates, one of those being MTBE. There was concern at that time about the potential health hazards effects of this chemical compound. The reports of health complaints included headaches, dizziness, nausea, and flu-like symptoms (Mayer, 1995). In the meantime, automakers worried about strict air regulation in large metropolitan areas recently approved by the Clinton Administration. The auto industry feared that the regulations would prevent them from complying with tougher efficiency standards.

By 1996, ethanol was using about 7 percent of the national corn production, and was blended to approximately 12 percent of the gasoline in the country. Complying with legislation mandating government fleets to buy alternative fuel vehicles, the Postal Service announced that it would buy 10,000 new delivery trucks, all of them flex fuel vehicles capable of running on E85 (market formation F5). However, according to postal service workers, most of the vehicles would run on gasoline, because of the small numbers of ethanol pumps throughout the country. Even where ethanol was available, the price was on average 10 to 15 cents a gallon higher than gasoline. This reveals a weakness of the downstream market, which despite developing some capability, proved to be unable to make use of the renewable fuel, or ethanol (-F8) . A Government Accounting Office report published in 1997 reported that the cost of the ethanol program since its inception in the 1970s was $7.1 billion, with no or minor benefit for energy independence and environmental quality. The report was considered a bad evaluation of the innovation of ethanol, lowering expectations about the future of ethanol as an alternative fuel (guidance of research -F4).

In 1997, a loophole legislation led automakers to launch flex fuel vehicles, but without much concern if the vehicles would really take on ethanol as a fuel. In other words, automakers invested to build capability in the downstream market without having much incentives about the availability of ethanol. Ford Motor Company announced that it would start selling flex fuel vehicles capable of running on ethanol or gasoline. Ford's effort was followed by Chrysler and GM. The initiative was criticized by environmentalists, because automakers were taking advantage of a loophole in the Federal Law, which offset CAFE[36] standards requirements. The credits for average efficiency, gave automakers license to sell more gas guzzling SUVs and vans, the most profitable line of vehicles at that time. At the same time, the sale of FFVs did not guarantee that consumers would fuel cars with ethanol instead of gasoline, environmentalists argued.

In Congress, the policy was favoring ethanol producers and the protection of the emerging ethanol market (guidance of research F4). The ethanol tax credit survived one

[36] http://www.epa.gov/history/topics/caa90/09.htm (07.06.2010)

more challenge in Congress. The industry's powerful lobby (Archer Daniels, the largest manufacturer and the National Corn Growers Association) gained support from lawmakers to keep the subsidies for ten more years. Congress extended the tax credit until 2007, despite the criticism that it cost US$ 600 million a year for American tax payers. Despite the favorable policy environment, the weak downstream market (capabilities in the downstream market -F8) hindered ethanol penetration in the market. Even with generous tax incentives, sales of ethanol were dismal, because of the lack of gas stations and pumps selling ethanol throughout the country. According to a DOE study, the United States had 385,900 alternative fuel vehicles, against 4 million in Brazil, 1.7 million in Japan, and 560,800 in the Netherlands. Alternative fuels in the DOE study included ethanol, methanol, compressed natural gas, and liquefied petroleum gas (derived from propane).

In 1999, ethanol saw new market prospects with the banning of MTBE in California. Considered an additive deemed to pose "a significant risk" to the environment, the state of California announced it would start phasing out the chemical compound, with total removal until 2002. In Massachusetts, the Department of Environmental Protection had detected problems with the use of MTBE, which when leaked was a potential source of water contamination (MTBE dissolves in water). An EPA panel suggested that the chemical should be phased out nationwide. At that time, MTBE was used in 85% of the gasoline sold in the US, while ethanol had the remaining of the market.

Translating the dynamics of innovation to the functions of innovations:

During the 1990s, positive expectations for ethanol increased because of the fuel's positive properties as oxygenate (research guidance F4). However, studies considered ethanol to increase smog levels during summer months (research guidance -F4). The Clean Air Act Amendment of 1992 required the mixture of

oxygenates into gasoline in 39 metropolitan areas. Toxicity problems with MTBE increased the potential market for ethanol in the late 1990s. Automakers put the first flex fuel vehicles (FFV) in the market (building of capabilities in the downstream market-F8), and governments required their fleets to run on FFVs (market formation F5). But these initiatives were not sufficient to spread ethanol growth outside the Corn Belt, because of the low number of service stations offering ethanol (-F8). The graph shows an increasing trend in the function market formation (F5) (government programs requiring ethanol use, government fleets using FFVs, and legislation renewing ethanol tax credits), and a steady negative trend on the function guidance of research (-F4) (ethanol's higher levels of volatility considered to worsen smog, and prevented ethanol from reaching the market year round). Despite some activity of the function building of capabilities in the downstream market (F8) resulting from the sales of FFV's, the lack of pumps in service stations selling ethanol drove the function down (-F8). Almost all FFVs used gasoline because of lack of infrastructure for distribution of ethanol.

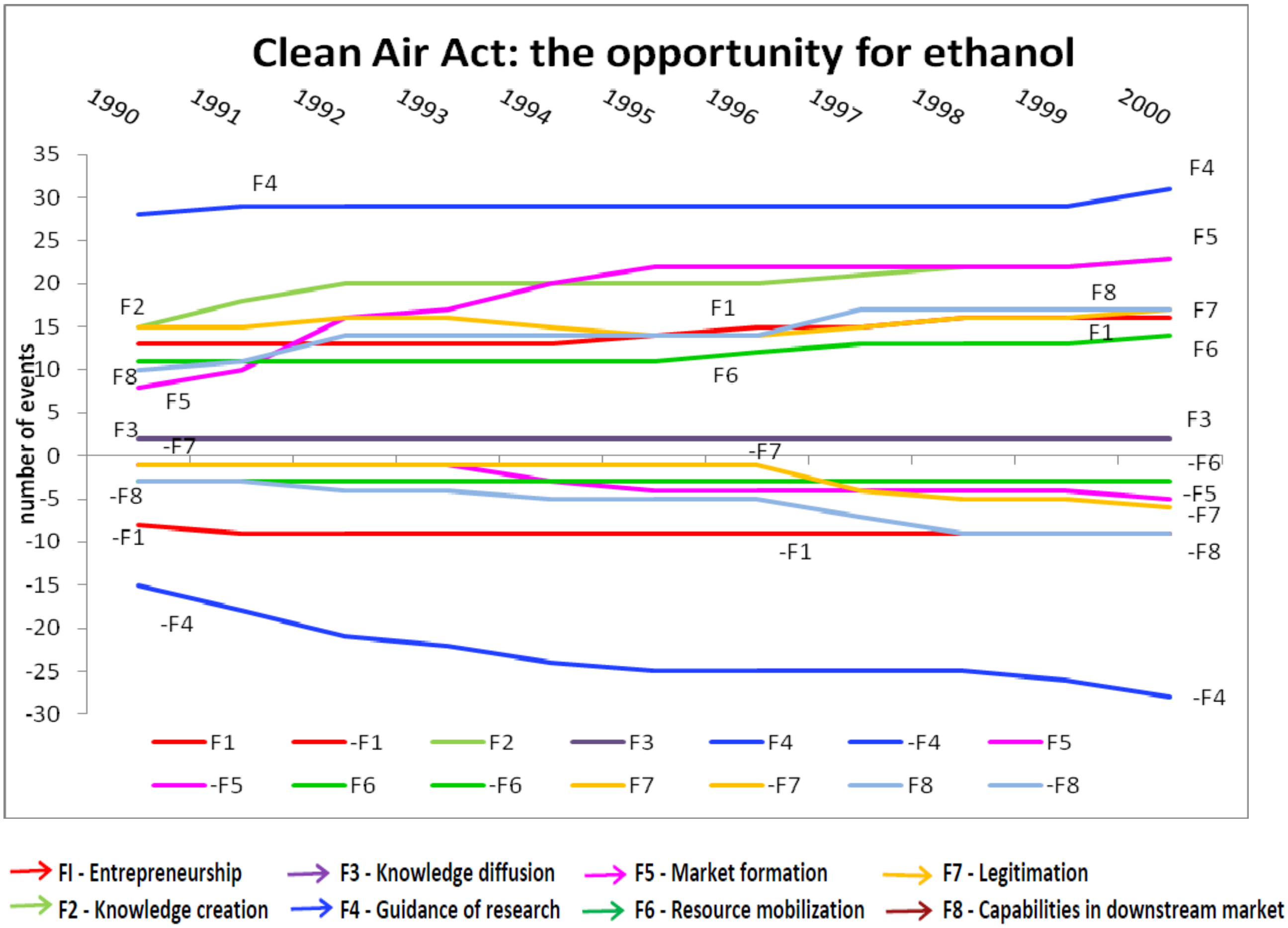

Figure18: Clean Air Act: the opportunity for ethanol. Map of the functions of innovation. 1990-2000. Source: NYT and Washington Post

6.4 The New Millennium: energy security, climate change. Reaching advanced ethanol (2000-2008)

During the late 1990s and 2000s, biofuels was recognized as a short term solution to address rising concerns of energy security and climate change. The positive expectations about ethanol (guidance of research F4) triggered a positive trend of activities in government research funding for advanced ethanol (knowledge creation F2; resource mobilization F6), market formation through the Renewable Fuel Standard (F5); and growing production of corn ethanol (entrepreneurial activity F1). However, the positive cycle of innovation was interrupted by lack of infrastructure for distribution and low sales of high blends of ethanol E85 (downstream market –F8), and by a general perception that growing ethanol production was responsible for increasing commodity food prices around the world (guidance of research –F4).

In the last period, environmental legislation required the use of oxygenates like MTBE or ethanol in major cities in the country. Ethanol became the only oxygenate in the market when MTBE was banned by the EPA. This requirement represented a mandate securing minimum market volumes for ethanol (market formation F5). The Energy Policy Act of 1992 (EPACT 1992) established E85 as an alternative fuels and required all government agencies to have flex fuel vehicles in their fleets. This government mandate (market formation, F5) was counteracted by a weak downstream market for ethanol (capabilities in the downstream market -F8). Most vehicles ran on gasoline, because of limited infrastructure for ethanol distribution at the pump outside the Midwest Corn Belt

In 2000, the policy framework reinforced the focus on advanced technologies to produce ethanol (guidance of research F4). The Biomass Research and Development Act created the biomass R&D initiative, a multi-agency program led by the Department of Energy and the Department of Agriculture to coordinate federally funded research of biomass, looking at the transportation, power, and chemical sectors (guidance of research F4; knowledge creation). One of the main thrusts of the program went towards R&D of ethanol from cellulose raw materials. One of the advantages of producing cellulosic ethanol instead of corn ethanol is that it prevents the farmers to divert the use of land from food to the fuel market[37]. One example of financing from this program was the partial funding of BC International, which announced the construction of the first

[37] http://www.brdisolutions.com/04/09/07

commercial plant to transform waste into ethanol. The new patented process used natural bacteria to transform wasted wooded material into alcohol. The new plant needed an investment of 90 million dollars, and took 18 months to be built.

The 2000 presidential campaign revealed once more the political significance of ethanol during the early stages of the campaign. Given the importance of the state of Iowa during the primaries, most candidates came to the corn state to provide legitimation to the technology (legitimation F7), and show their support to its most important business: ethanol.

In 2001, President W. Bush and his administration called for the use of biomass material from human, animal, and agricultural waste to increase the production of energy. The initiative expanded the research program to produce ethanol from sources different from feedstock like corn. The Bush administration energy plan called also for improved energy efficiency in a time when the Transportation department reported lower average economy for cars and trucks sold in the 2001 model year, a reflection of higher sales of sport utility vehicles. The Transportation department report predicted an average fuel economy of 24.5 miles a gallon, below the 24.7 miles a gallon reported for 2000. Because of the small number of service stations selling ethanol in the country (101 in a total of 176,000), most flex fuel vehicles (large part being SUVs) ran on gasoline, increasing the gasoline consumption in the country. These results did not reflect the efforts in tax incentives and environmental regulation the administration had been consecrating towards promoting the market for corn ethanol The efforts in market formation and research guidance could not have the expected positive effects on the innovation process of ethanol, because the weak capability of the downstream market prevented the alternative fuel to displace gasoline.

But the environmental policy framework was having a positive impact in the innovation of ethanol in California. To comply with Clean Air Act regulations, the federal administration required the state of California to blend all its gasoline with ethanol (market formation F5). The requirement came in the wake of the MTBE ban, an additive oxygenate used in most of California gasoline. California officials argued that ethanol would increase the price of gasoline in the state, affirming that refineries were developing technology that would produce less polluting gasoline without the need to use ethanol. They asked EPA for a waiver of the ethanol requirement. The California mandate preceded legislation that was being worked in the congress to broaden ethanol use as oxygenate nationwide. The bill had the support of the farmers lobby, and large ethanol producers who were also important political financial donors. The legislation increased expectations of market growth for ethanol (market formation F4), and would spur a wave of investments in the ethanol industry, in special in the Northeastern states (entrepreneurship F1; resource mobilization F6).

In 2002, Congress enacted legislation mandating the use of ethanol (market formation) the Senate passed an energy bill that expanded the amount of ethanol blended into gasoline nationwide. The Senate package also funded energy conservation and research towards clean sources of energy.

In 2003, New York City, the largest municipal fleet in the country, joined the Department of Energy's Clean City, a national program designed to promote the use of alternative fuels vehicles nationwide by mandating governments to replace their fleets with vehicles capable of running on alternative energy like ethanol, natural gas, or electricity. Meanwhile, the Energy bill remained stalled in Congress, as House and Senate were not able to compromise on some differences. One point of disagreement was related to the amount of tax credits given to corn ethanol. Those against the tax credits were concerned that lower tax on ethanol would jeopardize the tax funds going to the Highway Trust Fund.

In 2004, the Department of Transportation announced that it would extend the corporate average fuel economy credit to cars running on ethanol planned to expire on models 2004 through models 2005 – 2008. The agency claimed that the measure was set to promote the use of fuel ethanol and to decrease the US's dependency on imported oil. The measure was advanced, despite a congressional report, which had informed that only one percent of flex fuel vehicles used ethanol, and that the extension of fuel efficiency credit would increase gasoline consumption in 9 to 14 billion gallons over four years. In 2005, the U.S. had higher energy prices and was more dependent on imported oil. After almost ten years without major energy legislation, President Bush signed the Energy Policy Act of 2005, which included significant provisions for ethanol. EPACT2005 established the Renewable Fuel Standards (RFS), requiring that gasoline in the U.S. has an increasing amount of biofuels – ethanol or biodiesel. The RFS established the use of 4 billion gallons of biofuels in 2006, increasing incrementally to reach 7.5 billion gallons in 2012. The RFS replaced the Clean Air Act requirement to use oxygenates in reformulated gasoline, eliminating the incentive to use MTBE (Holt & Glover, 2006).

The enactment of EPACT2005 increased positive expectations about the ethanol market in the country (guidance of research F4). The state of New Jersey announced the construction of its first ethanol plant (entrepreneurship F1). The federal government contributed with US$ 1 million in grant money (resource mobilization F6). In New York City, the Environmental Protection Committee sponsored the clean car technology legislation that expanded the city's alternative fuel vehicle fleet. The legislation signed by Mayor Bloomberg required that 95% of cars, light trucks and vans bought by the city follow environmental standards as strict as the ones required in California. Connecticut promoted renewable energy by purchasing 575 alternative fuels vehicles for the state fleet, from which 528 were flex fuel and compatible to run on ethanol. The state planned to replace the remaining fleet vehicles by 2008.

The support towards corn ethanol received much criticism, as a solution that was risky and not sustainable in the long term. (guidance of research -F4) Critics claimed that most FFVs ran on gasoline because there were not enough ethanol pumps in service stations around the country (capabilities in the downstream market -F8). Trying to address this problem, Ford announced that it would finance the installation of ethanol pumps in the Midwest region of the country. The automaker said it would also increase the production of FFVs. With higher gasoline prices, and more tension in the middle-east, President Bush urged Congress to push for legislation that would stimulate the production of ethanol and other renewables (guidance of research).

In 2006, the debate about the benefits and costs of corn ethanol was heating up, triggering reactions from society, and from specialists in the field. The corn ethanol industry was blamed for hunger around the world (legitimation -F7). The combination of high oil prices, growing production of ethanol, and the jump in corn prices led to a strong criticism towards the ethanol industry, which became the main culprit for hunger around the world. Amidst strong criticism against biofuels, President Bush in his State of the Union made clear his support for renewable energy, and called for more R&D of advanced biofuels, those not using edible feedstocks (legitimation F7). Bush claimed that the U.S. had to decrease consumption of oil, saying that the United States was "addicted to oil".

Research and engineering was ongoing to make the process to produce ethanol more efficient and less energy intensive (knowledge creation F2). By placing ethanol plants close to cattle farms, corn residues called distiller grains were sent directly to cow feeding operations without requiring additional energy for drying operations. Moreover, the manure from cows were sent back to the plant and served as an additional source of energy. These engineering solutions brought significant gains in natural gas consumption, increasing the energy balance of ethanol production. The positive results brought raised positive expectations about the sustainability of ethanol as an alternative fuel.

Entrepreneurship was diversified in the industry (F1). Vinod Khosla, the founder of Microsystem, decided to enter the ethanol business by investing tens of millions of dollars in firms developing processes to produce ethanol using non edible biomass sources. Producers of enzymes like Novozymes and Danisco had made significant progress in reducing costs of enzymes for the production of cellulosic ethanol.

The industry was also investing in expansion. The largest one, ADM, having 25% of the ethanol market announced that it planned an expansion of 50%, which would place it with an installed capacity of 1.5 billion gallons throughout the following two years (entrepreneurship F1). Investments were increasing towards more advanced technologies to produce ethanol (resource mobilization). Goldman Sachs invested $27 million dollars in Iogen, the Canadian ethanol producer that was pursuing development of cellulosic ethanol. Investments in ethanol production sprung across the United States, mostly driven by generous tax breaks, increased demand of ethanol stimulated by the mandates, and expectations of large profits in the industry. Oil companies decided to invest in research of advanced ethanol. BP had announced investments of $500 million dollars in a research center that would develop technology and new processes to produce advanced biofuels (knowledge creation F2).

As the level of investment increased in the industry, so did the structure of the industry. While in 2003 half of the ethanol refineries were controlled by farmers, by 2006 80% of new ethanol production came from plants whose owners were not locals. New plants were large investments that were not necessarily linked to farming operations (resource mobilization F6). Many in Congress claimed that agriculture policy became independent from biofuels policy, therefore undermining the need for the tax credit.

Automakers continued to invest in the production of flex fuel vehicles, but the effort to build capabilities in the downstream market was undermined by the small number of ethanol pumps that could dispense the alternative fuel to those vehicles. Ford pledged that it would increase the production volume of flex fuel vehicles capable of running on ethanol or gasoline. General Motors was also a supporter of ethanol fuel, having used the Super Bowl in 2006 to kick off its campaign “Live Green, Go Yellow” to promote the use of ethanol and the use of FFV’s. DaimlerChrysler pledged to build

500,000 vehicles capable of running on ethanol until 2008. The big three at that time had around 4.5 million FFVs on the streets, but very few were running on E85. The automakers met with Congress and the President to ask for help to increase the number of ethanol pumps in service stations. From a total of 180,000 service stations nationwide, only 600 had pumps delivering E85. Oil companies were not encouraged to make the necessary investments to sell E85 as a fuel. At the market level, E85 received a negative assessment from Underwriters Laboratories, an independent product safety certification organization. UL stated that E85 was damaging pumps installed at service stations. UL and the Department of Energy held two days of hearings with the collaboration of oil companies, automakers and researchers to address the issue and develop a standard for pumps delivering E85. The certification problem delayed the proliferation of pumps across the country.

Increased production of ethanol, and better farm incentives changed the structure of grains production in the United States, with corn replacing much of the wheat fields. While in the 1970s American farmers accounted for half of wheat exports in the world, by 2006 its participation became less than a quarter. Technology, such the development of seeds for corn, soybeans, and cotton, also shifted production from wheat to these other crops.

By 2007, the rapid increase in the production of corn ethanol began to raise concerns about the potential impact of growing corn use for fuel production. Those issues created a negative expectation for the long term sustainability and development of the corn ethanol industry (guidance of research -F4). In fact, a study issued by the Earth Policy Institute predicted that in a few years ethanol would be using half of the American corn crop. According to estimates, the 79 ethanol plants under construction would double the ethanol capacity to 11 billion gallons by 2008. The estimate spread fears about the long term consequences for food supplies.

Counteracting the negative wave against corn ethanol, the Bush administration prepared a set of public discourses to strengthen the legitimation of ethanol and other biofuels (legitimation F7). Consistent with his rhetoric from 2006, President Bush used the State of the Union Address of 2007 to call for an increase in the mandate of biofuels. He also called for measures to increase the efficiency of cars and light trucks. President Bush made clear that his main goal was to decrease the country's gasoline consumption by 20% over the decade, and he believed that biofuels and efficient cars would help the US achieve this goal. More specifically, he established the target of using 35 billion gallons of biofuels by 2017, which would mean replacing 15% of the gasoline consumption for that year.

The wave of optimism about the future of ethanol market (guidance of research F4) spurred more investments in the industry (resource mobilization F6; entrepreneurship F1). Estimates indicated production of 6 billion gallons of ethanol for 2007, this volume coming only from corn. The industry was becoming less centralized in a large producer like ADM. At that time, the number of plants increased exponentially, pushing ADM's market share down to 25%. The new push for new biorefineries and new plants was good news for small cities in rural America needing to add to their employment figures.

At this time, the ethanol TIS enjoyed an increasing amount of resource mobilization (F6) and investments in research, development, and deployment (knowledge development F2; knowledge diffusion F3). The federal government showed commitment to support the scaling up, demonstration, and commercialization of advanced biofuels, by funding six demonstration plants developing processes to produce cellulosic ethanol. The goal was to reduce the production cost of cellulosic ethanol. According to the administration, the country would not reach the goal of producing 35 billion gallons of ethanol, using only corn. It was necessary to develop alternative processes using alternative feedstocks. The six companies winning funding were Broin, Abengoa Bioenergy, Alico Inc., BlueFire Ethanol, Iogen Corp, and Range Fuels.

Ethanol was being promoted in car racing for its superior power and torque when compared to gasoline. The IndyCar series would run for the first time the whole 2007 season cars fueled with 100% ethanol. GM decided to participate in the biofuels business, buying stakes in Coskata, a start-up company developing cellulosic ethanol at the demonstration stage. In the United States, it was the first time a car maker would enter the business of fuels.

In March of 2007, President Bush visited Brazil and talked to President Lula. The goal of the visit was to promote collaboration in biofuels and to develop joint programs to reduce demand for oil in the Western Hemisphere. The two countries signed a Memorandum of Understanding, which included R&D collaboration in biofuels, technology transfer to countries in the Caribbean, and development of international standards and certification of biofuels.

By the end of 2007, The Energy Independence and Security Act of 2007 reserved an important market niche for producers of ethanol (market formation F5). The Act, also known as EISA2007, expanded the Renewable Fuels Standards (RFS2), and established a volume of 36 billion gallons of biofuels in 2022. RFS2 also determined a ceiling for the use of corn ethanol, mandating the use of cellulosic biomass, or non-edible feedstock for the production of biofuels. In other words, RFS2 determined that 21 billion gallons of biofuels should come from advanced biofuels processes that would reduce the emissions of GHG by a pre-determined level (Yacobucci & Capehart, 2008). EISA2007 also established a new CAFE standard for cars and light trucks, setting an average mileage of 35 miles per gallon for models year 2020.

Following the government commitment towards the development of advanced ethanol technologies, the Department of Energy determined the creation of three Bioenergy Research Centers (BRCs) to develop research on biofuels produced from non-edible biomass (resource mobilization F6; knowledge creation F2). Each center would develop a specific capability in research. The DOE Bioenergy Science Center (BESC) would be led by the DOE's Oak Ridge National Laboratory, in Oakridge, Tennessee, and would focus on the study of resistance of plants, the cellulosic material breakdown into sugar, and the study of poplar and switchgrass. The DOE Great Lakes Bioenergy Research Center (GLBRC) would be led by the University of Wisconsin, in Madison, Wisconsin, and would focus on the study of plant conversion to sugars, and on the socioeconomic and environmental issues related to a biofuels economy. The third center, the DOE Joint Bioenergy Institute (JBEI) would be led by the DOE's Lawrence Berkeley National Laboratory, and would concentrate on less resistant crops, or model crops. The goal was to increase efforts and accelerate research into advanced biofuels to comply with the volumes required by RFS2.

In 2008, more incentives were given to promote the commercialization of advanced ethanol (guidance of research F4). The Farm Bill 2008 reduced the blender tax of corn ethanol from 0.54 to 0.45 cents per gallon, and established a new production tax credit for cellulosic ethanol of $1.00 per gallon. It also determined the provision of grants for the retrofitting and construction of biorefineries for the production of advanced biofuels. It required the US Department of Agriculture to support research to promote more sustainable farming and to promote the use of renewable energy in farms. The Farm Bill also determined joint work between DOE, USDA, and EPA to improve the necessary infrastructure for the production of biofuels, and provided ample funding for the research and development of bioenergy, including biofuels and bio-based chemicals (Capehart, Schnepf, & Yacobucci, 2008).

In 2008, gasoline was approaching $4.00 a gallon, and oil price surpassed $100 a barrel. Ethanol received much of the blame for the rise in food prices around the world, which played a negative role for the future prospects of innovation of ethanol in the short term (guidance of research -F4). Corn prices increased around 50% in one year, and soybean prices were projected to go up 30% as well. There were reports that bad weather and increased consumption in China were also contributing to high levels of grain prices. Food demand continued to grow worldwide, and the Department of Agriculture reported that based on interviews, some corn growers in the US decided to cut corn acreage for soybean crops.

Some scholars in the scientific community provided evidence against the long term sustainability of biofuels (guidance of research -F4). Still in 2008, the journal Science had published two articles arguing that over time, ethanol produced from corn would emit more greenhouse gases than gasoline. The first article authored by two researchers from Princeton University claimed that, over 30 years, corn ethanol would produce twice as much GHG emissions than gasoline. The second article, written by scientists from the Nature Conservancy and University of Minnesota claimed that the production of biofuels feedstocks triggered land use change in Asia, and in South America. The conversion of rainforests and savannahs in those places would be detrimental to the efforts to reduce climate change. Although many challenged the assumptions used by the researchers, these articles raised even more controversy about the sustainability of corn ethanol in the USA.

The downstream market was not capable of taking in the growing volumes of ethanol produced (building of capabilities in the downstream market -F8). Investments in distribution of ethanol did not keep pace with the overexpansion in the industry. The market was not able to absorb the additional supply of ethanol. The price of ethanol decreased 30% bringing an end to the era of ethanol boom. Verasun Energy, one of the largest ethanol producers and investors filed for bankruptcy (entrepreneurship -F1). Iowa, the core of corn ethanol business was also the center for the debut of candidate Barack Obama for the presidency of the United States. He campaigned in that state supporting the corn ethanol business in the region. He won the Iowa caucuses as a Democrat, marking his first victory for the presidential race.

Translating the dynamics of innovation to the functions of innovations:

Climate change and energy security became priority issues in the new millennium. Increasing volumes of ethanol production (entrepreneurial activity F1) and the launch of flex fuel vehicles (building of capabilities in the downstream market F8) raised expectations about the potential benefits of biofuels for the American energy problem (guidance of research F4). The positive expectation and the support of the administration led to additional research funding (resource mobilization F6) and the creation of a government program to manage research of advanced biofuels in the long term (knowledge creation F2), the Biomass R&D program. These initiatives, along with mandates for increasing volumes of biofuels in the long term (RFS2 mandated increasing volumes of advanced biofuels) (market formation F5), gave incentives for the construction of many new plants (entrepreneurial activity F1; resource mobilization F6)). Eventually, the bubble of investments was not matched with enough infrastructure for distribution (-F8). Despite sales of FFVs, most of them ran on gasoline (-F8). Ethanol was blamed for the rise in the price of commodity grains around the world, and the scientific community was not convinced about the environmental benefits of corn ethanol in the long run (-F4). The financial and economic downturn would take the innovation trajectory of ethanol to a difficult path beginning in the late 2008. The graph below translates the summary of events into the functions of innovation. There is a building up of all the functions of innovation in the positive side of the graph. However, some of the functions collapse on the negative side of the graph: 1) guidance of research (-F4), because of negative reports of ethanol: environmental sustainability and negative effect on food price; 2) building of capabilities in the downstream market (-F8): despite the increasing number of FFVs in the market, service stations did not have enough incentives to invest in ethanol pumps. 99% of ethanol sells as 10% blend with gasoline. Once sales of gasoline reach 10% of

gasoline market, they reach the "blend wall". Without the prospects of having a large market for E85, investors do not have enough incentives to take further risk in the business. Therefore, the collapse of the functions F4 and F8 (low expectation about the sustainability of corn ethanol and low penetration in the market of E85) may be preventing the building up of a virtuous cycle of innovation for the TIS ethanol. Without enough investments, cellulosic ethanol plants producing at the demonstration scale do not have the necessary resources to scale up to commercial scale, making more difficult the commercialization of advanced ethanol in compliance with the RFS2.

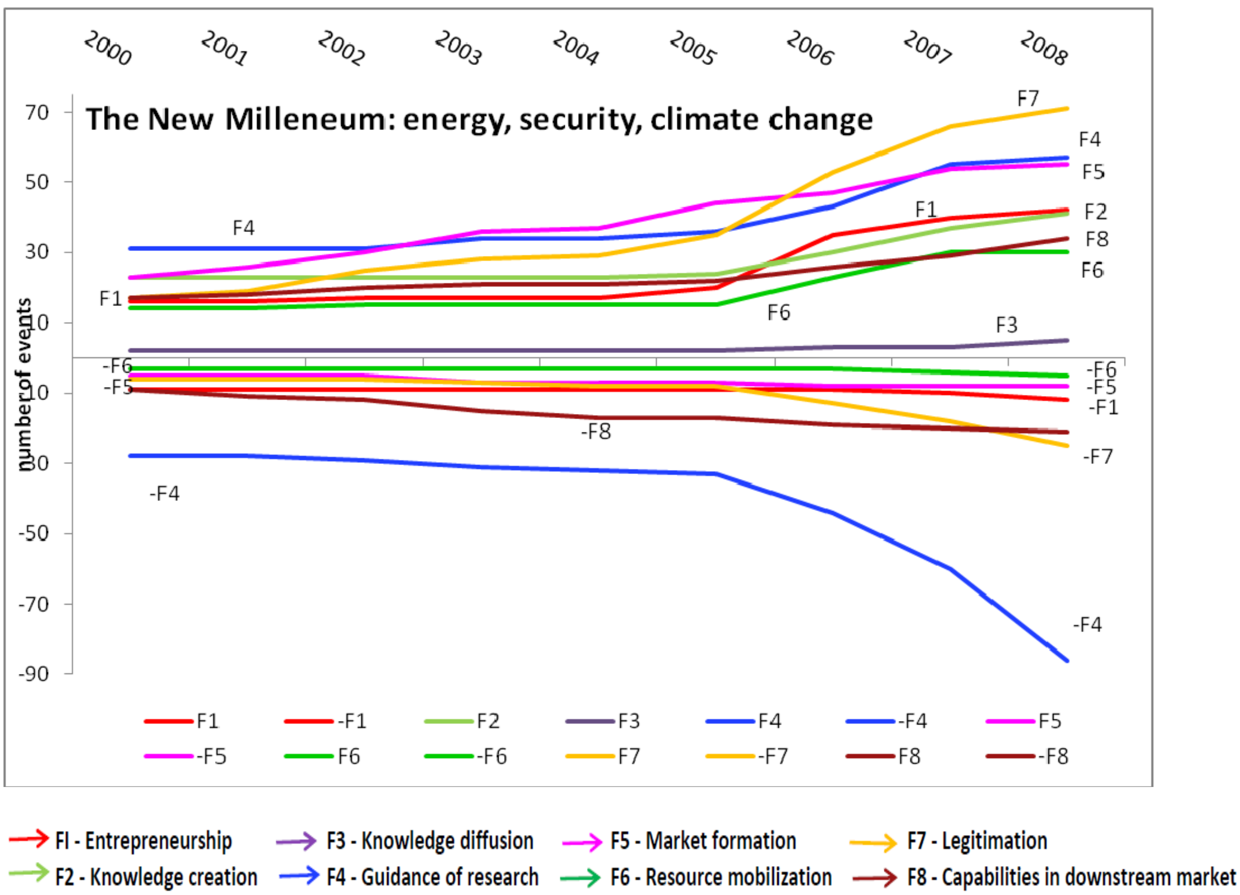

Figure19: The New Millennium: energy, security, climate change. Map of the functions of innovation. 2000-2008. Source: NYT and Washington Post.

CHAPTER 7

NARRATIVE ETHANOL BRAZIL

This chapter describes the trajectory of the ethanol innovation system in Brazil. It uses a narrative approach, based on the articles from the newspaper O Estado de Sao Paulo. The articles were compiled in chronological order, and complemented by gray literature. The unfolding of reports of events is presented in narrative form, and divided in the chapter in three different segments of time:

1) Proalcool under the military government
    a. Proalcool I – ethanol as a blend (anhydrous ethanol) and the development of ethanol engines (1975-1980)
    b. Proalcool II – hydrated ethanol and ethanol compatible vehicles (1980-1990)
2) The new Proalcool under the new democratic government – the process of liberalization, and the lost decade (1990-1999)
3) The flex fuel vehicle and the rebirth of the ethanol program (2000 – 2008)

Each session starts with a brief summary of main events, and ends with a brief analysis (in bold) relating the unfolding of events to the functions of innovation. The analysis is complemented by a graph showing the cumulative building or collapse of functions of innovations during the period.

A traditional producer of sugarcane and sugar since colonial times, Brazil started exploration of sugar-based ethanol in 1903, following a program created by the First National Congress on Industrial Applications of Alcohol (Moreira & Goldemberg, 1999). At first, alcohol was mainly used for the pharmaceutical and chemical industries, and for the production of the Brazilian rum popularly known as “cachaça”. By 1931, Brazil started to use ethanol with gasoline for the small transportation market in blends of 5% ethanol. In early 1970s, Brazil strong industrial growth was heavily dependent on imported oil. Around 80% of the gasoline consumed in Brazil was imported, representing $600 million in annual payments, a heavy financial and political burden for the Brazilian military government ruling the country at that time. With the Arab Oil Embargo of 1973, Brazilian annual payments for oil imports rose to US$ 4 billion, putting the country on an unsustainable financial path. In November of 1975, the military government launched the Alcohol National Program, or Proalcool (PNA). The program came as a relief for Brazilian sugar growers who were struggling to sell in an international depressed market (Azanha Ferraz Dias de Moraes & Rodrigues, 2006; J. Goldemberg, 2009).

Brazilians started doing research on engines running on ethanol and testing alcohol cars since the 1920s, but it was in 1975 that engineers from the government run research center Aerospace Technological Center (CTA) in Sao Jose dos Campos, state of Sao Paulo, unveiled a first prototype of the ethanol engine. CTA was developing a combustion engine designed to run on 100% ethanol.

Because sugar prices followed the international market, government had to fix ethanol prices to avoid that sugar mills would abandon ethanol production to sell sugar in more attractive markets. The government had to guarantee a minimum opportunity cost for ethanol production. The whole distribution would be centralized at the state owned oil company Petrobras at a price competitive to the gasoline, assuring a market for the additional production of ethanol by sugar and sugarcane producers.

7.1 Proalcool I: anhydrous ethanol as a blend and development of ethanol engines (1975-1980)

In Proalcool I, the military government assumed the role of entrepreneur (F1) and largest investor (resource mobilization F6). In addition to financing, major incentives for growing production came from a procurement policy, and the mandatory blending of gasoline with 20% ethanol (market formation F5). The funding for the development of the engine running on 100% ethanol (knowledge creation F2) began the process that would later lead multinational automakers to manufacture cars running on 100% ethanol (downstream market F8).

The National Alcool Plan mobilized a large amount of resources to the industry and the market, mandated the blending of gasoline with ethanol (market formation F5), and invested in the research to develop the engine running on 100% ethanol (resource mobilization F6; knowledge creation F2). Proalcool established the following mandatory policies: 1) procurement policy through Petrobras to guarantee the market and distribution for ethanol production; 2) loans and low interest rates to promote investments in ethanol; 3) the development of the engine running on 100% ethanol by CTA (Aerospace Technological Center). At its onset, the Brazilian Proalcool would allow the progressive blending of ethanol into gasoline up to 20%. The mixture did not require any change in the design of cars that ran on gasoline.

Brazil was active in developing knowledge in the automobile sector (knowledge creation F2). In 1976, first tests were made in buses (to replace diesel) and cars (to replace gasoline). Cars ran with hydrous ethanol (96% ethanol, 4% water). Ethanol also gained legitimacy in the racing car sector with the Brazilian Association of Pilots and Racing Cars claiming the use of cars running on ethanol in some of their competitions. Despite the positive prospects of the plan, many challenges remained, one of them being the standardization of the gasoline-alcohol blend throughout the country. According to automakers, standardization was important and critical in the design of an efficient engine. By September 1976, Volkswagen of Brazil, the largest multinational Brazilian automaker made the first demonstration of a car running on 100% ethanol to Brazilian authorities. CTA officially approved the car running on ethanol after a test of 4,000 kilometers that was considered successful.

The Brazilian centralized government used its financial power to finance the sugarcane and ethanol industries (resource mobilization F6). The Brazilian government through the state owned Banco do Brasil financed projects for Proalcool to increase sugarcane and ethanol capacity. However, the program was criticized in many fronts: many were skeptical that the whole substitution of gasoline by ethanol was feasible and realistic. There were already signs that projects were slow to be implemented and undersupply of ethanol was imminent. Sugarcane was considered the best feedstock to be used as an energy source. However, the government considered the potential use of manioc, because of the potential social and economic benefits of using this feedstock in rural communities.

By 1977, the blending of 20% ethanol into gasoline became mandatory in the metropolitan area of Sao Paulo. The new regulation represented an economy of 20 thousand barrels of oil per day for the country. Increasing demand was not matched by ethanol supply. The shortage of sugarcane and financial pressures led the government to prioritize the production of sugar in detriment to ethanol. Brazil still imported 80% of its oil consumption, and it had to maximize sugar exports to balance the country’s international trade. Despite the change in course, automakers remained committed to developing cars running on 100% ethanol.

7.2 Proalcool II: hydrous ethanol and ethanol vehicles (1980-1990)

During Proalcool II, automakers joined the ethanol innovation system and launched the first cars running on 100% ethanol (downstream market F8). The demand for ethanol grew fast (guidance of research F4), leading the government to accelerate the production and investments on sugarcane and ethanol (resource mobilization F6; entrepreneurial activity F1). However, supply would not fulfill demand (-F4), leading the government to order automakers to reduce production of ethanol cars (downstream market –F8).

The knowledge generated to build engines running on 100% ethanol helped to reinforce the downstream market for ethanol. By 1978, the technology to produce engines running on 100% ethanol had been developed and approved by CTA, but government officials raised questions on how to transfer the technology to the multinational companies without undermining the nationalistic character of the alcohol program. During the second phase of Proalcool, the government focused on the industrialization of cars running on 100% ethanol. Government and Anfavea, the national association of car manufacturers, fully collaborated on that task. A technical national commission was created involving the Ministry of Industry and Commerce, the National Council of Metrology, Standardization, and Industrial Quality, the Brazilian Association of Technical Standards, and the automakers. The commission guaranteed the proper planning and industrialization of cars running on 100% ethanol. The goal was to increase the exchange of information between research developed by CTA and the automakers. The commission decided that automakers would lead research on light-duty vehicles, while government through CTA would focus research on ethanol engines for public/mass transportation.

There were a number of incentives promoting the production levels of ethanol in Brazil (guidance of research F4).The federal government implemented tax incentives to stimulate the production of cars running on 100% ethanol. By early 1979, the Italian automaker Fiat announced that it had the technology ready to produce cars running on 100% ethanol, but needed government authorization to start production at industrial scale. CTA certified the product, since it fulfilled the basic requirements defined by the government R&D center: ethanol cars could not consume more than 15% than similar gasoline cars, and ethanol engines would have to deliver 20% more power than similar gasoline-run engines. In March 1979, Fiat started production of its model Fiat 147. Commercialization targeted at first government fleets, at the state and federal level. Brazil was consolidating its efforts and successfully building capabilities to promote the downstream market of ethanol (F8).

The government expected that the global demand of oil would exceed production by 1985. The National Commission of Alcohol had already approved more than 200 projects for additional production of ethanol through the construction of autonomous distilleries or distilleries annexed to sugar production plants. At this time, Brazilian sugarcane productivity was low by international standards, and most sugarcane production was dedicated to sugar production. The country had to create an infrastructure for the production of ethanol that would not compete with sugar.

The Brazilian president during the dictatorship accelerated the market formation of ethanol (market formation F5). The new president Joao Batista Figueiredo determined that all government fleets were required to run on 100% ethanol in the cities where there was distribution for the new fuel. The Italian automaker Fiat received the green light from CTA to produce and commercialize the Fiat 147 /alcohol car, which would be produced in mass scale in its plant in Betim, in the state of Minas Gerais. In the meantime, Sao Paulo, Brazil’s largest city, prepared to implement a program to transform its public transportation fleet (buses) to alcohol. The initial phase of the program tested four buses that were transformed to operate on ethanol. Tests were accompanied by CTA, as part of the Proalcool-motor program.

The government increased the ethanol blend to gasoline from 20 to 25%, the blend was previously approved by CTA to run on gasoline vehicles. This move reflected the government commitment towards proteting a niche market for the emerging ehtnaol system (market formation F5). With increased demand for ethanol, the Ministry of Industry and Commerce was already studying a plan to increase ethanol production by almost 10 billion liters by 1985 to replace diesel and heating oil. The government planned to produce 20.5 billion liters of ethanol, or the equivalent of 35% of oil imports.

In July 1979, the Brazilian government announced the norms governing the implementation of the second phase of Proalcool, assuring the private sector that ethanol production would be procured by the government, according to volumes and technical specifications defined by the Ministry of Industry and Commerce (guidance of research F4). Government prioritized investments following three main criteria: 1) lowest investment/installed capacity ratio; 2) best technological and economic utilization of feedstock, effluents, machinery, material that would optimize agricultural and industrial processes; 3) lowest cost in terms of adaptation of infrastructure necessary for the production and use of ethanol.

The multinational automakers Fiat and Volkswagen were certified by the Brazilian government and announced they were ready to produce alcohol vehicles at industrial scale. The government jointly with the national association of automakers, Anfavea, established a protocol that defined the quantity of ethanol-run vehicles to be produced, and the necessary volumes of ethanol required to be supplied to the market. Other multinational carmakers came onboard. General Motors do Brasil offered 22 cars running on ethanol to the state of Sao Paulo government for testing purposes. After two year testing, Ford do Brazil presented to consumers two of its models ready to be produced using ethanol as a fuel. The National Commission of Energy had approved the plan for the annual production of ethanol cars by automakers, beginning in 1980 with 250,000 cars, increasing incrementally to reach 350,000 vehicles by 1982. This had an important effect in the ethanol, raising positive expectations about the development of the ethanol industry in the short and medium term (guidance of research F4).

Knowledge creation was an important goal of policy makers in the Brazilian government (knowledge creation F2). Camillo Penna, Minister of Industry and Commerce, called for additional efforts to increase productivity and promote the technological progress of sugarcane and ethanol production. Government had also goals that went beyond volumes of production for automakers producing cars running on ethanol. Government and automakers signed an agreement by which car producers would work on R&D towards reducing the consumption of fuel by 20% until 1985. By the plan, the government would regulate the "retificas", or small auto-shops that were certified by the government to convert cars running on gasoline to ethanol. The Secretary of Industrial Technology would inspect and certify the shops.

From those early years of Proalcool, Brazil was already doing research on the production of ethanol using wood from sustainable forest cultures. The process to produce ethanol from wood was a research program led by the National Institute of Technology. The Agronomic Institute in Campinas, Sao Paulo, developed research using bamboo as a feedstock for the production of ethanol, showing promising results. CTA focused research efforts in developing ethanol engines to replace those running on diesel. One project in progress was the development of engines for commercial vehicles and farm machinery.

By 1980, Proalcool received criticism about its lack of social goals (guidance of research -F4). Proalcool was also criticized for being slow, with conflicting priorities, and lacking social focus. According to critics, the program concentrated wealth into few large sugar producers, and benefited the elite, which was already privileged by the sugar industry. Moreover, many large producers did not believe that the sector could achieve the production goals established by the government. The private sector demanded more action from the government to approve more projects to increase the installed capacity of ethanol production and sugarcane crops.

The process of building of capabilities in the downstream market has taken some difficult steps in Brazil. Trying to bypass excessive government regulation, many taxi drivers converted cars in unauthorized body shops and bought ethanol fuel directly from producers. Complaining against the high cost of engine conversion in shops certified by the government, taxi drivers started to adopt cheaper conversions that didn't change the engine's compression rate, therefore not taking advantage of the technology available to optimize the engine to run on ethanol. The adoption of these "backyard" conversions created a black market of engine conversions and ethanol sales, especially in the region of Sao Paulo. It also compromised the building of the appropriate capability so the downstream market was ready to take in the new and emerging technology (-F8). The government acknowledged that this was a reaction against the low speed of the program, but could not certify the informal technology because it increased the consumption of fuel by more than 40-50% in relation to gasoline. To make ethanol more available for consumers, the government authorized sales of ethanol in gas stations on Saturdays (as a result of rationing measures, gas stations remained closed for gasoline and diesel sale during the weekends). Despite the problems in vehicle conversion and fuel distribution, automakers reached agreement with the Ministry of Industry and Commerce to increase production of ethanol cars to 500,000 by 1981, signalizing the optimism of car producers over the future of the ethanol program.

The state of Sao Paulo was in steady economic development as a result of the ethanol and sugarcane expansion production. Entrepreneurial activity (F1) in ethanol was central to the economic development of the state of Sao Paulo. Over five years, ethanol production had increased more than 500%, from 362 million liters to 2.4 billion liters, bringing a significant economic and social impact to rural communities across the state.

The funding of this expansion was paid by the difference between the price of the gasoline paid by the consumer and the real price of anhydrous ethanol that was blended into gasoline. The price of ethanol was fixed at 65% of the price of gasoline. Automakers were also successful. By September of 1980, Fiat announced that for the first time sales of ethanol cars were higher than sales of gasoline vehicles. But Brazilians were aware of a broader debate around crop-based biofuels. Speakers at a conference alerted about the risks of intense use of feedstocks for energy purposes amidst the growing demand of food at the global level. The food versus fuel debate was a reality since the 1980s.

The heavy market control imposed by the military government had a negative impact in the process of innovation of ethanol. Consumers had to wait on average between 30 to 40 days to receive a model running on ethanol. This compromised the building process of the downstream market (-F8), Automakers announced that in 1981 they would be ready to produce between 600 and 700 thousands vehicles, representing 70% of the total production for the domestic market. Customers preferred ethanol cars because of tax advantage, better financing options, and good cost per kilometer ratio compared to gasoline. To assure enough fuel for ethanol cars, the government authorized the installation of ethanol pumps in all but one Brazilian state. To overcome the shortage of ethanol cars, many owners of gasoline cars began blending ethanol to gasoline in a 50/50 proportion, increasing the consumption of ethanol beyond what had been agreed between the government and the auto industry.

The use of ethanol was not only limited to the car sector. Experience with ethanol as a fuel was expanded to the rural market and to public transportation, expanding the range of knowledge creation to other applications in the transportation sector (knowledge creation F2; knowledge diffusion F3). In 1981, Chrysler of Brazil came out with the first truck running on ethanol. The company announced that it had invested more than 2.5 US$ millions in tests and equipments in the new technology. In the short term, the company planned to sell the new truck for distilleries, for the transport of sugarcane from the field to the mills. At the same time, the city of Sao Paulo initiated the tests with the first buses running exclusively on 100% ethanol.

With the OPEC decision to freeze oil prices, and the announcement that the government had already spent the resources allocated for the Proalcool, consumers became insecure about the availability of ethanol in the long run. Sales of ethanol cars decreased from 42,000 in January to 9,600 in May of 1981. The increase in the price of alcohol in relation to gasoline (the maximum relationship should be 65%[38] led consumers to prefer gasoline to ethanol. Other factors considered negative for ethanol cars included some technical problems that dealers had not been able to address at this point. Those events inhibited sales of alcohol cars in the short term, and compromised the building of capabilities in the downstream market (-F8).

To stimulate the sales of ethanol vehicles, representatives of auto industries met with government authorities to suggest a change in price that would reflect an advantage for ethanol in relation to gasoline for consumers. Authorities did not decide anything about price, but made clear that Proalcool would focus only on light duty vehicles and would not include large vehicles such as buses, and trucks. The government explained that the technology was not ready for this kind of transportation mode. The government decided to increase the price difference between gasoline and ethanol for consumers, and to provide more tax incentives to stimulate sales of ethanol cars. At the same time, authorities decided to eliminate the certification seal requirement, a bureaucracy that represented an additional step for the consumer. The elimination of the seal, however, would facilitate the illegal use of ethanol in gasoline cars. Despite the new government incentives, some specialists argued that those measures had not addressed technological problems. Most consumers who had their cars converted from gasoline to ethanol in body

[38] Because of the lower energy content of ethanol, the government established the ethanol should not be beyond 65% of the price of gasoline.

shops were having numerous technical problems. These problems were affecting overall consumer's perception and were undermining the public confidence in the ethanol technology, therefore compromising the whole legitimacy of the program.

Automakers and government made efforts to regain confidence. Their strategy was to increase the incentives for the ethanol car and regain consumer's confidence (guidance of research F4; building of capability in the downstream market F8). But sales of ethanol cars improved when the price gap between gasoline and ethanol had increased at the pump. A market research revealed a correlation between technical complaints of ethanol cars and the price gap between the fuels. The larger the price gap, the smaller the number of complaints. Following the positive results, the government decided to increase tax benefits to taxi drivers, reducing in 28% the price of vehicles for these consumers. It also decreased interest rates for taxi drivers. The National Commission also established that all distilleries financed by Proalcool would be required to have all their vehicles adapted to run on ethanol. As a result, industry announced increased sales of alcohol cars. The advantages provided to taxi drivers took them to the dealers instead of making them transform their engines in small shops or "retificas". At this point, it was the end of the line for the business of "retificas". Thanks to increased sales to taxi drivers, the market share of ethanol cars in the total sales of cars raised to 40%, a substantial jump from 10% registered in the previous year.

These actions described in the last paragraph had a positive effect in the innovation system of ethanol in Brazil (research guidance F4; building of capability in the downstream market F8). The participation of ethanol vehicles in the total car sales reached almost 80%. The government announced that since its beginning, the production of sugarcane increased from 75 million tons to 212 million tons, supplying the production of 7 billion liters of alcohol. This amount replaced the equivalent of US$ 2 billion in imported oil. The consumption of oil derivatives decreased 6.3% in the first quarter of 1983 compared to the same period of 1982, while the consumption of ethanol increased by almost 55%. This allowed a reduction in oil imports of 17.5%, according to the government. Technical problems were being addressed. Collaboration between the Institute of Sugar and Alcohol and the giant Usiminas developed a new technology capable of neutralizing the corrosion caused by ethanol in industrial equipments The new technology, subject of a patent, should replace the use of additives in plants and tubulation, reducing as a result the production cost of ethanol. Later, Ford would test the technology in its cars. The non corrosive alcohol, as it was called, decreased the production cost of cars and the production cost of ethanol, since it did not require the use of special equipment to avoid the effects of corrosion caused by alcohol.

By 1985, 96% of cars produced in Brazil were designed to run on 100% ethanol, and reports confirmed that consumers were getting increasingly confident about the technology and performance of the alternative fuel vehicle. The government then designated a working group to formally evaluate the performance of Proalcool, including members of the National Commission of Alcohol, The Institute of Sugar and Alcohol, The National Oil Council, Petrobras, Secretary of State Owned Companies, and the Ministry of Finance. The group would set the stage to promote a better coordination among the leaders of the program, and to improve the dialogue among the many agencies and actors involved in the decision making process.

Even facing lower oil prices in the international market, the Brazilian government remained committed to investing in ethanol (resource mobilization F6). From 555 thousand liters in 1976, the production jumped to 11.4 billion liters in 1985 (entrepreneurship F1). A large sum of investments went to research for sugarcane and industrial processes (knowledge production F2). R&D results brought new cane varieties, and new and more efficient industrial processes and production systems. The use of the distillation waste, or “vinhoto” as a fertilizer in the field or in the production of methane gas was also a notable progress in the ethanol mill (guidance of research F4).

In 1986, Brazil consumed more ethanol than gasoline. Petrobras was critic of government subsidies to ethanol. The state owned company pressured the government to decrease the difference between the price of gasoline and the price of ethanol, since the company was responsible for subsidizing the price difference, which paid for the Proalcool deficit. The government assured the population, especially ethanol car owners, that ethanol would remain 35% cheaper than gasoline, and announced an increase in the production of the alternative fuel. By mid-1987, the mill Santa Elisa in the city of Sertaozinho, in the region of Ribeirao Preto, state of Sao Paulo began producing newly developed hydrous non corrosive ethanol at industrial scale. After being tested by automakers, the new product was available for consumers at gas stations. But the next paragraphs will show that the days of the ethanol car would be counted because very soon the supply of ethanol would not be able to fulfill the high demand. This whole process compromised future prospects of ethanol development (guidance of research - F4).

In 1989, the consumption of ethanol surpassed production, and supply became a problem. Despite the installed capacity of 16 billion liters, sugarcane was prioritized for the production of sugar. Even if government and ethanol producers had an agreement to produce 12.3 billion liters of ethanol, it was clear that the industrial sector was disrespecting the agreement and was directing a larger part of sugarcane for the production of sugar attracted by increasing international prices. To make matters worse, the low supply of ethanol fuel decreased the price difference between gasoline and ethanol to 21%. In ten years, the difference between gasoline and ethanol decreased from 41% to 21%. Lines to fill up the tanks with ethanol were already a common scene in some large cities in Brazil. With this scenario, the government announced that it would limit production of ethanol cars, leading consumers to look for solutions to convert their cars from ethanol to gasoline. Ethanol began to be rationed in many Brazilian cities, and the production of ethanol cars became 45% of the total car production, a large slump from 80% registered recently.

To compensate the undersupply of ethanol, Brazil began importing methanol from the United States, and ethanol from the European Union. Other measures to limit the domestic consumption of ethanol included the reduction of gasoline-ethanol blends from 22 to 12%. The government also decided to pay 11% more to producers to stimulate them to produce higher volumes of alcohol. The supply was already critical in the states of Rio de Janeiro, and other states in the Center South region. To deal with the ethanol shortage, some gas stations had to sell ethanol blended with imported methanol. Sales of ethanol cars went down 20% in only two weeks, even if cars were sold at a large discount price. Translating the dynamics of innovation to the functions of innovations:

In the first phase of Proalcool, the federal government gave all the incentives to spur entrepreneurial activity (F1) through procurement policy (market formation F5), loans and low interest rates (resource mobilization F6), and the development of the ethanol engine (knowledge creation F2), (downstream market F8). There was skepticism that the government plan would be successful (guidance of research-F4). But government counteracted pessimism with strong regulation, and investment (resource mobilization F6). The market for ethanol was secured with a mandate to blend all gasoline with 20% ethanol (market formation F5).

The second phase of Proalcool began with the successful launch of the ethanol car (downstream market F8), leading to increasing demand of ethanol, thus increasing investments (resource mobilization F6) for increased production (entrepreneurial activity F1). The government also approved higher blending to gasoline (from 20 to 25%) (market formation F5), increasing demand for anhydrous ethanol (guidance of research F4), leading the government to invest more in production (resource mobilization F6, entrepreneurial activity F1). The government focused on increased efficiency (knowledge creation F2), and better infrastructure

for distribution and use of ethanol (downstream market F8). All multinational automakers joined the Proalcool and launched ethanol cars (downstream market F8). But Proalcool was criticized for being slow. Supply of ethanol cars and fuel did not match high demand (-F4). The program was expensive, because the government had to subsidize the price difference between ethanol and gasoline for the consumer (-F4). With the lack of ethanol in service stations, the government-led program lost credibility among drivers of ethanol cars and automakers (-F4). The graph below shows the building up of almost all functions of innovation. There is a strong build up of capabilities in the downstream market (F8) – ethanol car; of research guidance (F4) – positive results and good expectations, government setting policy targets; and market formation (F5) – procurement policy, blending mandates; of knowledge creation (F2) – development of engine running on 100% ethanol, tests of cars running on ethanol, improvement of ethanol. However, with the lack of ethanol to fulfill demand, the government ordered freezing of ethanol cars production. Functions F8 and F4 collapse to the negative side of the graph. The ethanol program almost came to a halt for lack of ethanol to supply the high demand.

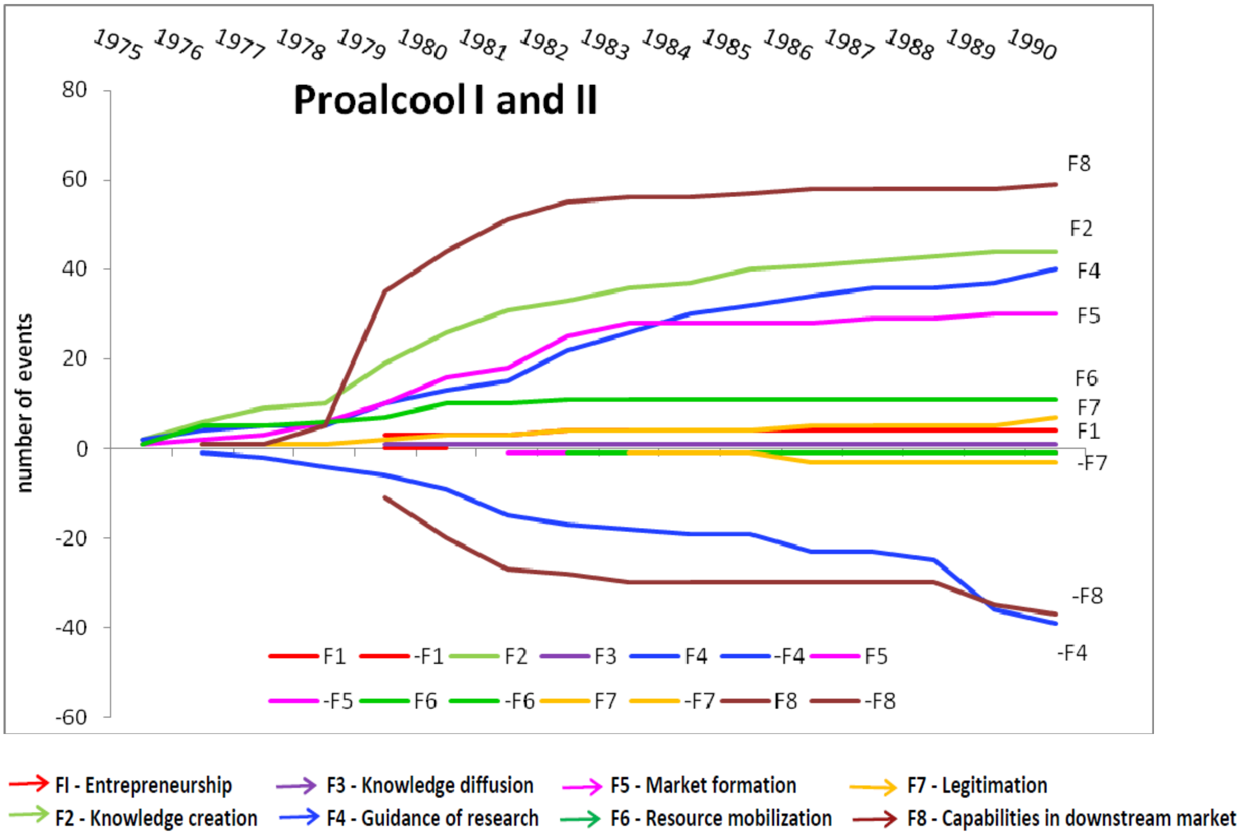

Figure20: Proalcool I and II. Map of the functions of innovation. 1975-1990.
Source: O Estado de Sao Paulo

Between 1985 and July of 1990, the participation of ethanol cars in the domestic sales of automobiles went down from 84.8% to 4.87%. The picture from the newspaper <u>O Estado de Sao Paulo</u> depicts consumers desperate to sell their ethanol cars.

7.3 The New Proalcool and the new democratic government (1990-2000)

During the 1990s, ethanol cars almost disappeared from the Brazilian market (downstream market –F8). Following the shortage of ethanol in the market, automakers shifted production to gasoline cars. Automakers joined the new ethanol plan (in process of deregulation) when the government mandated federal fleets to switch from gasoline to ethanol cars (market formation F5). Taxi fleets followed suit, attracted by generous tax incentives (downstream market F8). Despite government efforts, volumes of production of hydrated ethanol for dedicated engines remained small. The largest part of ethanol production went to the market of anhydrous ethanol, used as a blend at 20 to 25%.

The 1990 Iraq invasion to Kuwait and the onset of the Gulf crises exacerbated tensions in the oil market, bringing new hopes to the ethanol program. Government and ethanol producers reached an agreement to guarantee volumes of ethanol necessary to satisfy demand. The worsening of the Gulf crises and the prospects of an imminent oil crisis (with consequent higher gasoline prices) had an immediate psychological effect, pushing consumer's preference back to ethanol.

The recently elected president Fernando Collor de Melo announced a new energy plan, supporting the creation of a new Ethanol Plan, or a new Proalcool, but this time without any government protection (guidance of research F4). The president promised to promote the competitiveness of ethanol through more investments in R&D. At the same time, the president also announced an increase in the production of oil in the country. Ethanol producers put together a media campaign to regain consumer's confidence and promote the legitimacy of the technology (legitimation F7).

The 1992 United Nations Conference on Environment and Development took place in Rio de Janeiro. It became the perfect event to showcase the Proalcool program to the rest of the world. The event helped to highlight the environmental advantages of ethanol as a potential replacement for gasoline. In 1993, the Brazilian congress approved a bill that would allow the Brazilian government to start regulating emissions from automobiles. In addition to all the measures to control pollution, the law secured the market for ethanol (market formation F5), by mandating that all the gasoline in the country be blended with 22% ethanol.

By 1994, only 10% of vehicles produced in Brazil were ethanol compatible, down from 26% in 1993 and 91% in 1985. Automakers lost confidence in the government, questioning the reliability of ethanol supply to the market. In addition, ethanol producers had no interest in producing alcohol because of high prices of sugar in the international market caused by a supply cut by India and Cuba.

The 20th anniversary of Proalcool in 1995 was celebrated with many questions about the long term future of the program. Despite the technological advancements, ethanol production costs were still high to compete with gasoline. Moreover the program was criticized for lack of transparency and no accountability for practices of corruption. In the automobile sector, the industry focused on popular models. The low confidence in the supply of ethanol fuel led automakers to produce the popular models, the "populares", only with gasoline compatible engines. By the end of 1995, ethanol cars made 2% of the total fleet produced for the domestic market. In 1996, the percentage went down to 1%. Despite the low production, automakers kept investing in engineering and development of ethanol engines (knowledge creation F2). The project of engines running on ethanol for the popular models was ready, and improvements in technology showed that by using higher compression rates, ethanol engines were able to yield more power compared to similar gasoline engines (guidance of research F4).

The end of the 1990s saw the deregulation of Proalcool, and the implementation of policies to promote the market of ethanol (market formation F5). By 1997, the government announced the beginning of the deregulation of the Proalcool. The government stopped regulating prices. Petrobras stopped centralizing the distribution of ethanol to gas stations, and would soon stop to subsidize the program (average of US$ 1.2 billion per year). Ethanol producers would negotiate prices directly with distributors. President Fernando Henrique Cardoso announced measures to stimulate the consumption of ethanol by creating incentives to convert taxis and the government fleet from gasoline to ethanol compatible engines. The program would be financed by consumers through the enactment of a "green tax" on gasoline cars.

An American Coalition of Governors led by Wisconsin Governor Tommy Thompson visited Brazil to know in more detail the Brazilian experience after 22 years of Proalcool and forge an international collaboration between the two countries. Americans were interested in the production of flex fuel vehicles stimulated by law, and to increase the production of E85 to address the oversupply of corn in the Corn Belt region.

The rebirth of the Proalcool came in a moment when there was an oversupply of sugarcane in Brazil especially during the harvest of 1997/1998. The positive perspective of the ethanol industry (guidance of research F4) led to more collaboration between industry and university to improve the efficiency in the production of ethanol (knowledge creation F2; knowledge diffusion F3). The University of Campinas developed a process that increased the productivity of plants by using new materials and eliminating steps in the process. Sugarcane and ethanol producers increased adoption of residues and sugarcane bagasse to reduce energy consumption and production costs. Research collaboration was taking place at the international level as well. The University of Sao Paulo and University of Florida started a collaboration to use genetic engineering to convert residues and sugarcane bagasse to ethanol.

Despite R&D efforts, ethanol was not yet competitive with gasoline without subsidies. Since gasoline and diesel consumers paid the price difference, it was urgent to find a solution to increase the competitiveness of ethanol. With higher sugarcane productivity and a good season, the production of sugarcane was expected to increase significantly in the coming years. But the government did not have a long term plan for the sector. Brazil had limitations in the sugar export market because of the protectionist policy of developed countries. There were many in the government who believed that ethanol should serve only as an additive to be blended to gasoline up to 25% and to diesel up to 15%, the limits considered environmentally safe by CETESB, the environmental regulatory agency of the state of Sao Paulo. The private sector demanded definitions from the government.

Despite the lack of definitions (guidance of research –F4), long term research remained active. Researchers at the University of Campinas were able to improve the process of production of ethanol from molasses, setting up a continuous process for the fermentation stage of ethanol production.

By 1998, with the oversupply of ethanol and lack of a growing market, the government decided that Petrobras would buy the excess production of ethanol and start building a strategic stock of the fuel. The government insisted in the problem of competitiveness of ethanol in relation to gasoline, and reiterated the government support of the plan without subsidies to ethanol. Without subsidies, ethanol was still more expensive than gasoline, and the prospects of relaxing the oil monopoly in the country would open the possibility of cheaper gasoline in the domestic market, putting more pressure in the competitiveness of ethanol.

To stimulate the market of ethanol, the government increased the gasoline-ethanol blend from 22% to 24%. The Brazilian Ambassador in the US discussed the possibility to start ethanol imports to the state of California in the US, following the banning of MTBE, considered a toxic additive to gasoline. Brazil tried to negotiate the reduction of import duties of 60 cents a gallon imposed on Brazilian ethanol. The potential market of ethanol in California would solve the oversupply problem of ethanol produced in Brazil.

The government implemented the law promoting the use of ethanol in government fleets and taxis (market formation F5).The incentive to ethanol cars became law. The Senate Commission approved a plan that mandated the conversion of the federal government fleet from gasoline to ethanol. The plan financed loans and tax incentives to consumers buying ethanol cars. GM announced that it would resume production of ethanol cars, taking advantage of government incentives to consumers. This time, there was an oversupply of ethanol in the market. Moreover, GM would produce ethanol cars using the direct injection system that the company's engineers were able to adapt to ethanol cars. In the following months, automakers would increase sales of ethanol cars to fleet owners, and to consumers in the ethanol and sugar business. The downstream market became stronger again (F8).

The transition to a deregulated market brought uncertainty to the sugar and ethanol sectors. The competitive producers who had invested to modernize their industrial plants were eager to compete in a liberalized market economy. Those who were less productive preferred to take advantage of government subsidies and price protection. In December of 1998, the government announced a decrease of 72% in the subsidy paid to ethanol producers. The government would instead buy the ethanol surplus available and build a stock to help balance ethanol prices in the market.

By 1999, Brazil produced 15 billion liters of ethanol, most of it was anhydrous ethanol to be blended with gasoline at 24%. A small part was sold as hydrous ethanol for a fleet of 3.5 million cars running exclusively on ethanol. The change in the mix from hydrous to anhydrous ethanol resulted from the fall in the sales of ethanol cars during the previous ten years. The change in the ethanol mix led service stations to return to gasoline pumps, reducing the number of ethanol pumps in approximately 50%. This move was detrimental to the process of building of capabilities in the downstream market (-F8). To increase the demand of ethanol, the government decided to increase the percentage of ethanol in gasoline from 24% to 26%.

Twenty years after the first ethanol car was sold in the Brazilian market, it was clear for the government and industry that the success of the program resulted from the price advantage of ethanol in relation to gasoline, and from the technological progress that solved most of the technical problems of the first ethanol vehicles. The technological progress was possible because tax incentives and subsidies throughout the whole supply chain (agriculture, industrial and automotive) allowed the whole sector to learn and improve the technology. The crisis in the sector was triggered by undersupply of ethanol (producers lost interest because the international sugar market became more attractive than ethanol). Consumers became insecure about the supply of ethanol in the gas stations. They stopped buying ethanol cars, putting the whole program into a halt. At the same time, low gasoline prices led automakers to produce gasoline cars. However, ethanol still remained in the market as 22-26% mixed with gasoline in its anhydrous form, and in a smaller amount to fuel the fleet of the remaining ethanol cars still circulating in the market. Automakers had made important technological progress with gasoline cars, which became more efficient and economic.

By the year 2000, the international price of oil went up, and ethanol became more attractive for consumers. In 2001, 131 ethanol industrial plants in the state of Sao Paulo produced their own power from bagasse. From those, 12 produced a surplus that was sold to the grid. The surplus was estimated to be equivalent to the energy sufficient to power 270 thousand homes in a monthly basis during the sugarcane harvest. This became a win-win outcome for government and industry, since consumers would be able to buy this additional power during the months of drought when supply of energy from hydropower was less reliable. Translating the dynamics of innovation to the functions of innovations:

During the 1990s, the participation of ethanol cars in total production went down to 1% of the entire Brazilian fleet (downstream market -F8). Automakers shifted production to gasoline cars, which had become more efficient. The government started the deregulation process of ethanol, but without long term policy goals (guidance of search -F4). The production of ethanol remained stable; volumes of hydrated were replaced by sales of anhydrous ethanol for blending with gasoline in 24-25% (market formation F5). The market size was limited by the size

of the gasoline market. A generous crop of sugarcane in 1998 resulted in oversupply of ethanol, making the government to create new outlets for ethanol. The government implemented programs to promote the market such as converting government and taxi fleets to ethanol compatible cars (market formation F5). Industrial plants became more efficient, and research focused on improving the competitiveness of ethanol (knowledge creation F2). However, the ethanol plan still lacked a long term policy target (guidance of research -F4). The graph depicts the low activity of functions of innovation during the 1990s. There is a slight building in knowledge creation (F2); market formation (F5) – government program converting government and taxi fleets to ethanol; capability in the downstream market (F8) – automakers resuming production and sales to government and taxi fleets. However, during the lost decade, ethanol cars' participation in the market fell to 1%, explaining the collapse of F8 (downstream market).

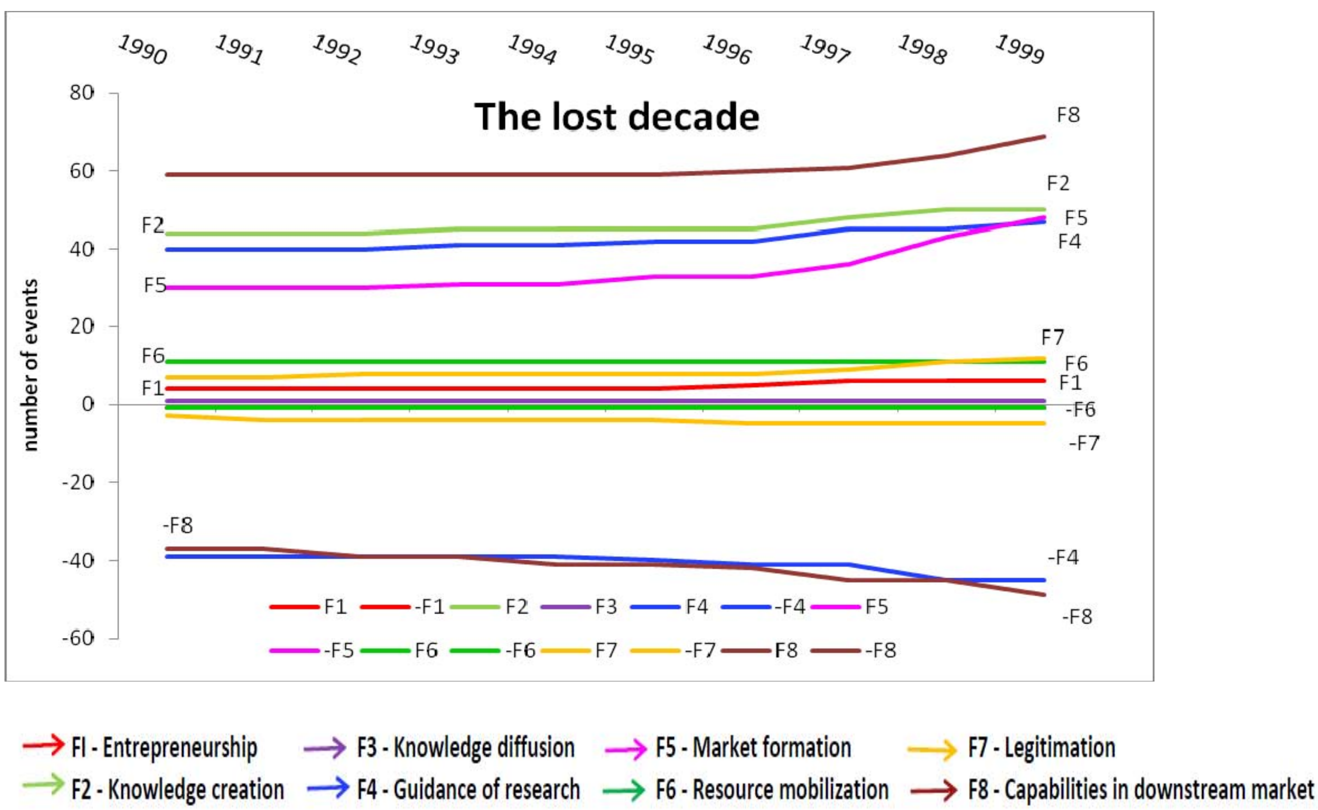

Figure21: The lost decade. The map of the functions of innovation. 1990-1999.
Source: O Estado de Sao Paulo.

7.4 *The flex fuel vehicle and the rebirth of the ethanol program (2000-2008)*

During the 1990s, the ethanol industry went through a long process of price liberalization. Despite technological progress, ethanol still could not compete with gasoline without subsidies. With the production of higher volumes of sugarcane (entrepreneurial activity F1), there was an oversupply of ethanol in the market, leading automakers to resume production and sales of ethanol cars to government and taxi fleets, which switched to ethanol cars following government mandates and fiscal incentives (market formation F5; downstream market F8). But it was only in 2003, when the automobile industry launched the flex fuel vehicles (knowledge creation F2; downstream market F8), that the ethanol innovation system was able to rebound and take a sustained development path. Higher gasoline prices and a more competitive ethanol industry helped consumers regain credibility in ethanol as an alternative to gasoline (guidance of research F4). Positive expectations led the government to further invest in research (knowledge creation F2) and promote collaboration (knowledge diffusion F3), attracting private investments in the industry (resource mobilization F6; entrepreneurial activity F1), setting the stage for a positive cycle of innovative activity.

In the year 2000, the Brazilian ethanol TIS resumed building the capabilities of the downstream market (F8). Ford presented the prototype of the flex fuel vehicle (FFV), with technology developed in its headquarters in the US, and adapted to Brazilian needs. The prototype could run with any percentage of ethanol or gasoline. The company also demonstrated an engine capable of running with ethanol or compressed natural gas. The government provided support for the new technology, by giving FFVs the same tax incentives received by ethanol cars. The National Association of Vehicle Producers (Anfavea) announced that flex fuel vehicles would be ready for commercial sale in one year. The cars would cost a little higher than ethanol cars, but would benefit from the same tax benefits (3% advantage in relation to gasoline cars). The technology was based on software that identified the fuel and calibrated the engine according to properties of the fuel being used. Two firms competed with the technology: Magnetti Marelli, and Bosch, both international firms. The technology, however, was developed entirely in Brazil, based on the concept developed in the US[39]. Both firms wanted to sell the software to automakers VW, Fiat, and GM, as well as Ford who would also compete in the market.

The flex fuel vehicle became available in 2003. The first car to be commercialized was the Gol Total Flex. GM came out with its first model in flex fuel, the Corsa 1.8. Consumers were informed and advised that the economic advantage of using ethanol was when the alternative fuel's price was at 70% or below the price of gasoline. The positive perspectives of FFVs revived the interest for ethanol and sugar business (guidance of research, F4). The sector soon had a positive wave of investments, 1 billion Brazilian reais, to increase production in the short term (resource mobilization F6; entrepreneurship F1).

The building of capabilities in the downstream market was also supported by Petrobras, which soon recognized the importance of building pipelines going from the production site to ports. These pipelines would be exclusive for the transportation of ethanol (F8). Predicting higher exports, Petrobras started to invest in infrastructure to transport ethanol from the production location (most of it in the center-south region) to major ports. The company's goal was to expand pipelines for the exclusive use of ethanol sold to the external market. Improvements in flex fuel technologies were ongoing. Magneti Marelli (MM) was performing research on a technology that allowed a vehicle to use 4 different fuels: ethanol, natural gas, gasoline blended with ethanol, or pure

[39] Brazil uses gasoline already blended with ethanol up to 26% and hydrated ethanol, while the US uses pure gasoline or blended with 10% ethanol, or E85 – 85% anhydrous ethanol and 15% gasoline.

gasoline. The new technology would allow Brazilian manufacturing centers to export vehicles to other countries in Latin America.

The stronger downstream market (F8) gave support to the growing ethanol and sugarcane sectors, which enjoyed a strong entrepreneurial moment (entrepreneurship F1; resource mobilization F6). In 2004, all automakers had models in FFVs. After VW and Fiat, Ford introduced its first model flex fuel, and the French Renault announced its first FFV car, the compact Clio. In the first year of sales, automakers predicted that FFVs would reach 15% of total vehicle sales in the Brazilian market. The positive estimate gave impulse to the sugarcane industry, predicting a 7% increase in the harvest for the following year. Contemplating imports from Brazil, China and Japan made investments in the Brazilian transport, research and production infrastructure. Japan invested US$ 15 million in the Biofuels Technological Pole in the city of Piracicaba, an industrial and research center of biofuels in the state of Sao Paulo. The rapid development of the FFV market and sugarcane production came with strong criticism to the Brazilian government for its lack of planning and leadership. To avoid large fluctuation in the price of ethanol, the government created a regulatory framework to regulate supply and demand of ethanol during sugarcane harvest (8 months a year) and during ethanol production (during the whole year).

In January 2005, the sales of FFVs accounted for 30% of sales of new cars (light duty vehicles). Investments continued in the ethanol industrial sector. Industries from the state of Sao Paulo began expanding towards the border of the state of Sao Paulo and the state of Mato Grosso do Sul. Bosch announced its ongoing research to improve the performance of the FFV system. The new system would eliminate the small gasoline tank to help start the engine when temperatures were below 18 centigrade. With the new technology, ethanol would be heated before injection in the combustion chamber. The new system would be less expensive, because it would require less equipment in the car. In the production line, automakers gave more flexibility to the flex technology. VW and

GM placed in the market the tri-fuel system, allowing engines to run on natural gas, gasoline, or ethanol. With record sales of FFVs (in July, FFVs made 60% of total sales) and increasing consumption of ethanol, production of ethanol reached the limit of its installed capacity (sugarcane and ethanol). From the installed capacity of 20 billion liters, production was 18 billion liters. Specialists confirmed that the expansion in ethanol demand was proof that most consumers fueled their FFVs with ethanol, and not with gasoline. Consumer feedback pointed to the economic and technological advantages of ethanol against gasoline.

In the research front, the production of knowledge and formation of networks between academia and the private sector assured the successful continuation of the innovation process in ethanol in Brazil (knowledge creation F2; knowledge diffusion F3). A collaboration between the Technological Sugarcane Research Center in Piracicaba, a Network of Brazilian Universities (Ridesa), the Sao Paulo Agronomic Institute, and the private research company Canavialys (owned by the Brazilian Group Votorantim) focused on the development of new sugarcane varieties that grew in the savannahs of the Northeast, a region poor in soil nutrients and with recurrent drought periods. Embrapa, the Brazilian Agro Company announced its Bioenergy Plan, which focused on 5 main groups of research: forests, biogas, biodiesel, ethanol, and residues.

More entrepreneurial activity (F1) supported by a stronger downstream market F8). Until the end of 2006, 19 new ethanol plants were operating, and 89 projects for new plants were being studied. Petrobras and the Government of the state of Goias, a state where great part of the expansion was taking place, signed an agreement to build a pipe line, allowing Petrobras to transport efficiently the ethanol produced in that state to the export terminals in the eastern coast of the country. The additional production was not yet enough to satisfy the increasing market demand, especially during the months considered off-season for the industry (outside the sugarcane harvest). The result came with higher ethanol price at the pump, leading consumers to switch back to gasoline. In the meantime, Brazil and the US joined efforts to collaborate in the field. They created the Inter-american Commission on Ethanol to forge collaboration in research, commercialization and technological development of bioenergy within the Americas.

In 2007, an agreement between the government of São Paulo and the National Institute of Metrology and Apex Brazil, the Export Agency, marked the first long term effort to create standards to facilitate ethanol exports. The goal was to transform ethanol fuel in an international commodity. Following the creation of the Inter-american Commission on Ethanol, The United States and Brazil began work to promote collaboration. The two countries expressed their intention to sign an agreement to collaborate to increase their production of biofuels and decrease their dependency on foreign oil. For that matter, President Bush came to Brazil in March 2007 to sign an agreement and discuss bioenergy with President Lula of Brazil. The two countries would collaborate in technology transfer, R&D, and standardization of biofuels. Despite the positive perception of the Brazilian ethanol program around the world, R&D players in Brazil pointed out that Brazil was still a laggard in investments in R&D in the sugar and ethanol sector, investing only US$ 1.2 per hectare, while Argentina invested US$3, and Australia invested US$ 10.

The positive trend of entrepreneurial activity and investments in the sector remained stable in Brazil (entrepreneurship F1; resource mobilization F6). The Brazilian National Bank of Social Development (BNDES) announced investments of 10 billion Reais. The investment was part of a 20 billion Reais investment plan, the amount necessary to build 100 new plants to increase production of ethanol in Brazil. The remaining investment would come from the private sector until 2010. In the same year, the harvest of sugarcane reached the highest level of its history, raising questions about the sustainability of the Brazilian ethanol program. Specialists alerted about the growing migration of sugarcane harvest to pasture lands, and the dangers of monoculture. The debate around food vs fuel led President Lula to commission a study to the United

Nations FAO, which revealed that biofuels did not affect negatively the production of food in Brazil.

To avoid unsustainable practices of a one crop agricultural program, the Brazilian government developed a plan to certify the production of sugarcane and ethanol following the sustainability requirements established by the international market. The plan would require the rapid implementation of mechanized harvest, decreasing the burning of sugarcane fields before harvest, a practice that emits a significant amount of greenhouse gases. The sugarcane producers made an agreement with the government of Sao Paulo to end burning of sugarcane fields in 2014, as opposed to 2031 as established by law. For land with inclination higher than 12%, considered to be more difficult to implement mechanized harvest, end of burning would happen until 2017.

Europeans became interested in the Brazilian FFV technology. France announced the new Megane flex, showcasing an engine able to run on E85. The technology was developed in collaboration between French and Brazilian engineers. Peugeot Citroen Brazil would export FFV engines to their French headquarters. With the internationalization of the Brazilian ethanol, UNICA, the Brazilian association of sugar and ethanol announced the opening of its international offices in the United States and Europe.

In addition to investments in production capacity, there was a positive trend towards investments in research and development (entrepreneurship F1; resource mobilization F6; knowledge creation F2). Cosan, the largest ethanol producer in Brazil consolidated its dominance in the Brazilian ethanol industry announcing the acquisition of ten new ethanol plants. The Spanish group Abengoa bought three plants from the Brazilian Dedini group, increasing the international investment in ethanol and sugar production in Brazil. BNDES announced its financial support to the ethanol and sugar sector, pledging investments of 25 billion Reais until 2011. In the same year, Brazil saw a significant wave of investments in research. Dedini, the largest producer of equipment for the production of sugar and ethanol in Brazil signed an agreement with FAPESP, the R&D financing agency for the state of Sao Paulo, to invest 100 million Reais in R&D of sugarcane and ethanol. The investment funded research on cellulosic ethanol from cane bagasse. Embrapa, the government led R&D agriculture company focused research efforts on sugarcane trangenics. The largest Auto Show in the world in Germany showcased the first motorcycle with flex fuel engine developed in Brazil, and also showcased vehicles with flex fuel technology imported from Brazil.

The Brazilian government had plans to upgrade the infrastructure of the Amazon region to promote development in the region. The English newspaper Guardian criticized the plans, arguing that they might place the tropical forest in danger in a period of 40 years. The Brazilian Agriculture minister and the ministry for the environment discussed about the prospects of sugarcane crops in the degraded areas of the Amazon region. Coca-Cola had already a small production of sugar in the region. The United Nations criticized the development of sugarcane plantations in the Amazon region. The Brazilian government then created a commission to define a policy (ecologic zoning) on how and where to plant feedstock for biofuels in the Amazon region.

Years of investment in R&D brought significant results to the sugarcane and ethanol industry (guidance of research F4). In the beginning of 2008, years after having sequenced the DNA of sugarcane, Brazilian scientists were able to sequence the DNA of the yeast used in the fermentation of most of the processes of ethanol production in Brazil. And the Ministry of Agriculture formalized the long term strategic commitment of the Brazilian government in the ethanol and sugar sector. A study published by the Ministry declared that in 10 years Brazil would increase ethanol production by 120%, with exports growing by 223% during the period. Following the European Union interest in biofuels, Brazil and the European Union continued negotiations for the certification of ethanol produced in Brazil. Europeans wanted to make sure they would not import Brazilian ethanol that was produced without certain environmental requirements.

But the fast growing trend of sugarcane and ethanol production did not come without resistance from the scientific community (guidance of research -F4). A Science magazine article surprised many stakeholders in ethanol and sugar business in Brazil and in the rest of the world. The article provided support for the argument that the continuing production of biofuels would bring serious consequences for the environment. According to the article, taking into the account the damages to the Amazon forest for increased production of soybeans, it would take 320 years for biofuels to present a positive environmental benefit. In the case of the savannahs in Brazil, there would be a negative CO_2 balance resulting from the destruction of native plants for additional production of biofuels.

Despite the negative media for biofuels, the production of ethanol from sugarcane was soaring in Brazil. According to specialists, the 2008/2009 harvest would dedicate more sugarcane for ethanol than for sugar. (guidance of research F4). Following agreements with the state of Sao Paulo, almost 50% of the 2007/2008 sugarcane was mechanically harvested, eliminating burning of sugarcane fields, a practice known to be damaging for the environment.

The market of FFVs continued evolving. After 5 years it was introduced, flex fuel vehicles accounted for almost 90% of car sales in the domestic market (guidance of research F4). Consumers had used more ethanol than gasoline, because the biofuel provided economic advantages compared to gasoline. The advancement of flex technology and increasing sales of FFVs was already considered the main factor driving sales of ethanol in Brazil. In February of 2008, the sales of ethanol (1.43 billion liters) were higher than the sales of gasoline (1.41 billion liters) in the country. This trend was a positive result for the ethanol industry, and kept investors interested in participating in the innovation process of ethanol in Brazil (guidance of research F4; resource mobilization F6).

The Brazilian government remained committed to research and to the development of advanced technologies for ethanol production. The federal government was investing 150 million Reais in five years in a research center (federally funded) to do research and development on advanced ethanol technologies (knowledge creation F2; resource mobilization F6). The CTBE, Technology Center of Bioethanol would undertake its own research, and would also serve as a users facility for universities and firms willing to test their lab experiments at the pilot scale.

Despite the international attacks on biofuels, ethanol continued to receive record investments from international and national entrepreneurs. Investments increased 16% from previous years, with plans for 32 new plants. Oil companies were also interested in the Brazilian ethanol business. BP had acquired half of the stakes of Tropicana Bioenergy and invested 1.6 billion Reais to finance investments in sugarcane and ethanol in Brazil. Cosan, the largest ethanol producer in Brazil invested in distribution and retail by acquiring all Esso (Exxon) stations in the country. The prospects for ethanol in Brazil were positive. Petrobras announced plans to invest in biorefineries that would be integrated with biomass. The oil giant Shell announced plans to invest in sugarcane ethanol and in cellulosic ethanol, acknowledging the company’s interest to enter the business of biofuels in Brazil. With new investments, ethanol production would increase 15 to 19% compared to the previous year, and fuel approximately 5 million flex fuel vehicles available in the Brazilian market. Specialists claimed that approximately 80% of FFVs used ethanol instead of gasoline.

Brazilian engineers were working with automakers in the US and Europe to diffuse the knowledge developed in Brazil to other countries. Citroen Brazil was exporting flex engines to France and Sweden, while GM had nine Brazilian engineers from the Brazilian branch working in the American headquarters to help the US improve the flex fuel technology. Brazil had also a partnership with the European Union and Sweden to test the performance of ethanol in buses in the city of Sao Paulo.

R&D investments between academia and the private sector were applied to advance technologies for the production of ethanol (knowledge production F2; knowledge diffusion; resource mobilization F6)). In the industrial side, The Federal University of Rio de Janeiro continued its R&D efforts on the development of cellulosic ethanol. The goal was to find an affordable enzyme, which could effectively break the molecule of cellulose from the sugarcane bagasse at commercial scale. The Research funding agency of the state of Sao Paulo announced the bioenergy program, with initial investments of 73 million Reais in new technologies for the development of biofuels. The investment would be complemented by the private sector, the federal government, and the state of Minas Gerais. At the federal level, the government would fund 45 institutes (270 million Reais in the three first years) to pursue research on bioenergy through a collaborative network.

Brazil had also plans to invest abroad, and announced investments in the African continent. The plan was to build 18 ethanol plants in Sudan. A study estimated that Brazilian exports of ethanol should increase threefold until 2015, consolidating Brazil as the largest ethanol exporter in the world. Looking at the Japanese market, and the new law requiring blending of 3% ethanol into gasoline, Petrobras acquired a Japanese refinery and announced plans to distribute gasoline blended with 3% ethanol (E3) to the Japanese market. The operation would be done through the recently created Japan-Brazil Ethanol, a company formed by the Brazilian Petrobras and the Japanese estate owned Nippon Alcohol Hanbai KK.

Following the investment boost in ethanol plants, sugarcane reached the mark of 70% of the harvested area in the state of Sao Paulo, leading the state government to block any further expansion of sugarcane crop in the state.

The international financial crisis which began in 2008 made the planned investments a more difficult reality, because of the lack of credit in the international market. Many companies delayed their investments, and the Brazilian market would see some consolidation to survive the challenges of the financial market. With the economic downturn, gasoline prices went down, putting pressure in the competitiveness of ethanol. Translating the dynamics of innovation to the functions of innovations:

The development of the flex fuel technology in Brazil (knowledge creation-F2, capabilities in the downstream market-F8), adapted from the technology developed in the U.S, allowed the innovation process of ethanol to rebound and regain credibility (guidance of research-F4). Having the distribution infrastructure in place (capabilities in the downstream market-F8), consumers did not have problems to find ethanol in service stations. Higher gasoline prices and enough ethanol supply helped ethanol to gain competitiveness in relation to gasoline. The positive prospects of ethanol (guidance of research-F4) attracted investments in production (mobilization of resources-F6), and in additional research (knowledge creation-F2) in collaboration with domestic and international partners (knowledge diffusion-F3). Despite the debates about the sustainability of ethanol (-F4, -F7), Brazil seemed to have entered a positive cycle of innovation. The graph below shows all the functions of innovation building up (F4 and F8 slightly moving down in the negative side). Oversupply of ethanol and high gasoline prices change expectations about the future of ethanol in the Brazilian market (F4). At the same time, the development of the flex fuel car as a capability in the downstream market (F8) reinforces positive expectations about ethanol (F4), providing conditions for long term policy guidance (F4), research and collaboration with partners (F2, F3), giving long term assurance to private investors (F6) and ethanol producers (F1) about the sustainability of the market demand (F4). The government and private sector played an important role educating and informing the consumer about the advantages of using ethanol over gasoline, guiding the consumer to make the correct decision at the pump (legitimation F7). Once a positive cycle of innovation was set

in, all the functions of innovation were fulfilled and interacting to further the process of innovation.

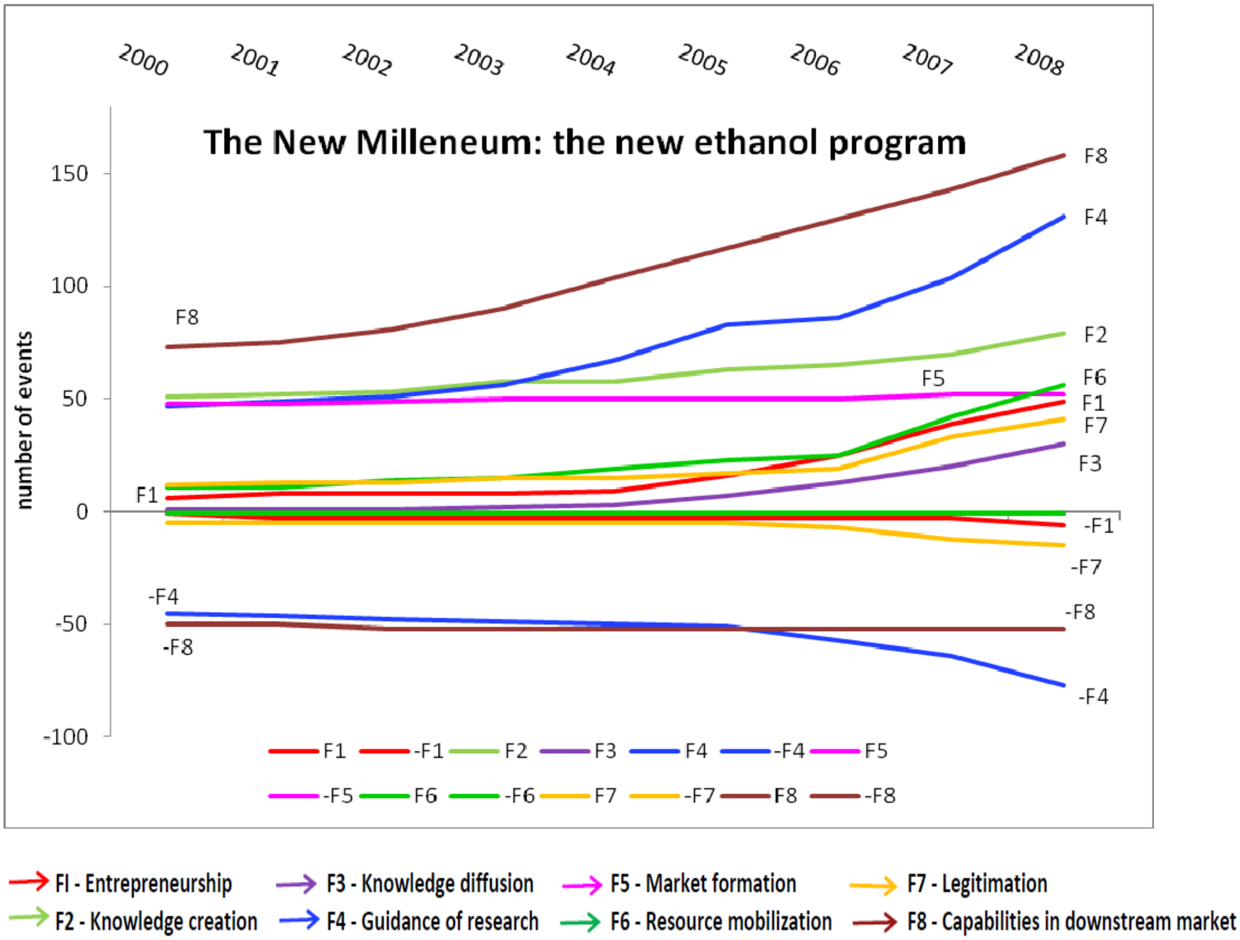

Figure 22: The New Millennium: the new ethanol program. 2000-2008. Source: O Estado de Sao Paulo

CHAPTER 8

COMPARATIVE ANALYSIS

Since Brazil was under a dictatorship at the onset of Proalcool, the Brazilian state played the role of entrepreneur in the beginning of the period. During the 1980s, entrepreneurial activity was negative (plants shutting down, producing less) or nonexistent in Brazil. The financial and economic crisis of late 1980s and 1990s led the Brazilian government to decrease incentives to Proalcool. Moreover, lower oil prices and high international sugar prices decreased the private sector appetite for big projects in ethanol. Imbalance between supply and demand caused undersupply of ethanol during the late 1980s and early 1990s. Unable to find ethanol to fuel their cars, Brazilian consumers did not trust the ethanol program and switched to gasoline only cars. Ethanol volumes remained stable thanks to a Brazilian law that required blending ethanol to gasoline in percentages ranging from 24 to 25%. Entrepreneurship regained strength after the successful launch of FFVs in 2003.

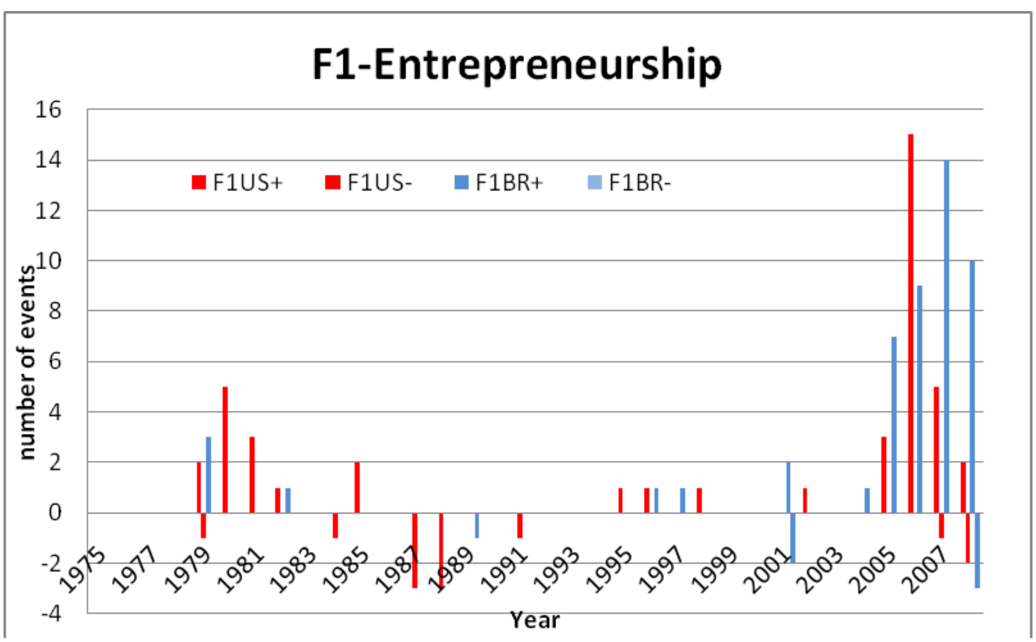

Figure 23: Entrepreneurship (F1) U.S. and Brazil - number of articles reporting events on ethanol

In the U.S, entrepreneurship was positive during President Carter years. Ethanol innovation enjoyed policies supporting the development of gasohol. Like in Brazil, during the 1980s, entrepreneurial activity was negative or nonexistent. President Reagan ended or decreased resources for energy programs focusing on renewable energy. There was some entrepreneurial activity under President Clinton, following the Clean Air Act of 1990, and its amendments in 1992 establishing E85 (ethanol 85%, gasoline 15%) as an alternative fuel. Strong entrepreneurship emerged after the Energy Policy Act 2005, which established the Renewable Fuel Standards, or mandates to use ethanol at the national level under a long term growing incremental schedule.

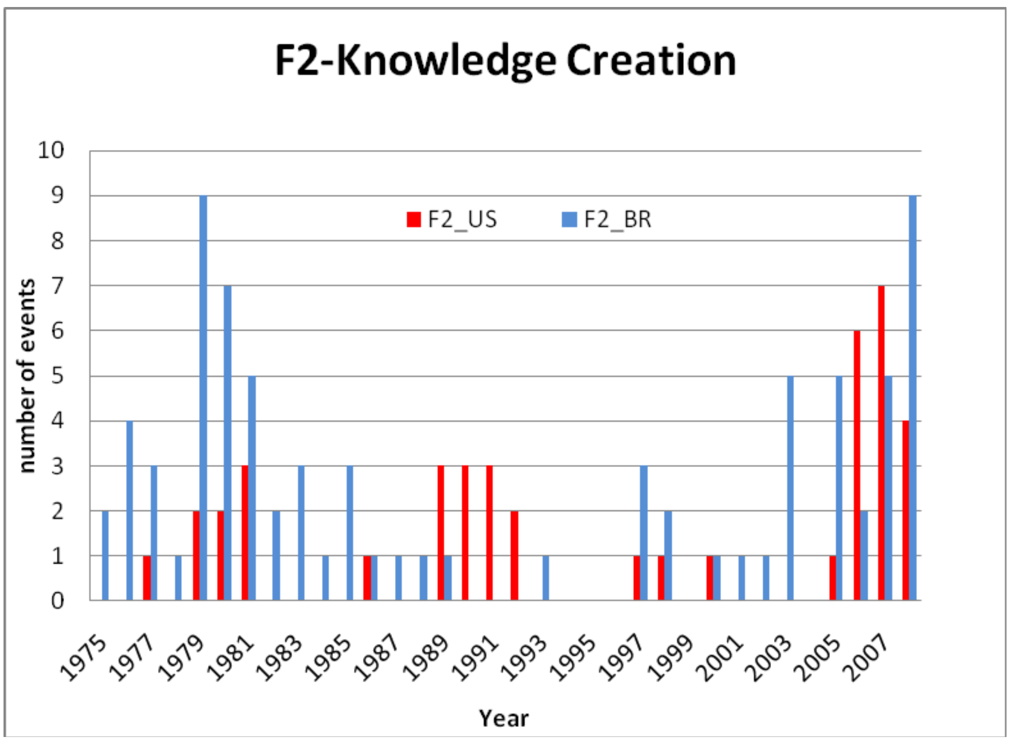

Figure24: Knowledge creation (F2) U.S. and Brazil- number of articles reporting events on ethanol

Brazil dominates knowledge creation (F2) most of the years. Since knowledge creation relates to the whole supply chain (agricultural, industrial, and automobile sectors), Brazil performed better than the U.S. because of all developments and tests performed with engines and automobiles running on 100 % ethanol in the first period, and later with the developments with the flex fuel technology. The U.S. grows fast in knowledge creation after the Energy Policy Act of 2005, establishing the first Renewable Fuels Standards, and a strong government support to fund demonstration plants of cellulosic ethanol.

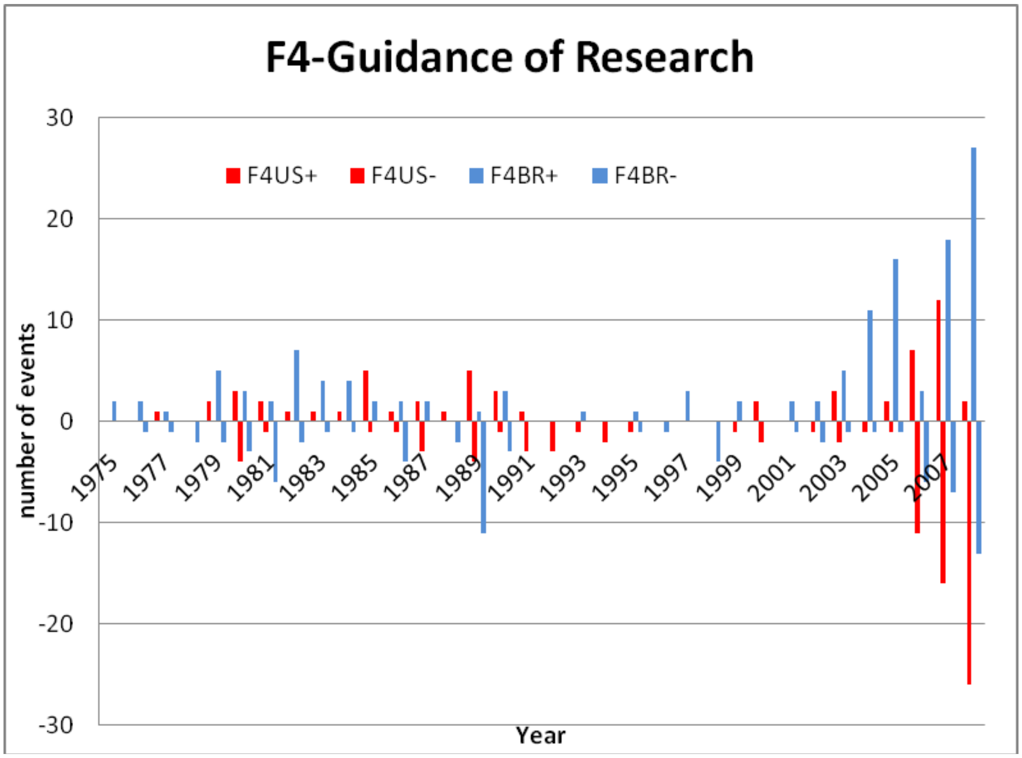

Figure25: Guidance of Research (F4) U.S. and Brazil - number of events reporting on ethanol

There is not a trend pattern for guidance of research (F4) for either country until the early 2000s, the period when the Brazilian ethanol takes off. Most reports of events from the late period relate to the debate around the social and environmental implications of biofuels. The Brazilian ethanol was able to prevent long term damage, therefore continuing to generate positive expectations about the technology. It is still fighting some criticism about the implications of increased sugarcane production to deforestation and to the environmental degradation of the region of “cerrado”, or the Brazilian savannah. The same cannot be said about the U.S. Since the technology in the U.S uses corn as the major feedstock, the U.S. process became vulnerable to strong criticism from academia and international organizations about the environmental impact of its use in substitution of gasoline. Corn ethanol has on average a worse environmental performance in measures of carbon emissions than sugarcane ethanol from Brazil. Moreover, sugarcane use as a fuel is not considered to be detrimental to the food market. Therefore, corn ethanol has been more vulnerable to the food versus fuel debate, which has affected negatively the long term innovation activity in the sector. In the U.S., the policy target moves towards advanced and cellulosic ethanol (not yet available at commercial scale), while in Brazil most entrepreneurial activity is concentrated on sugarcane ethanol (rapid return on investment).

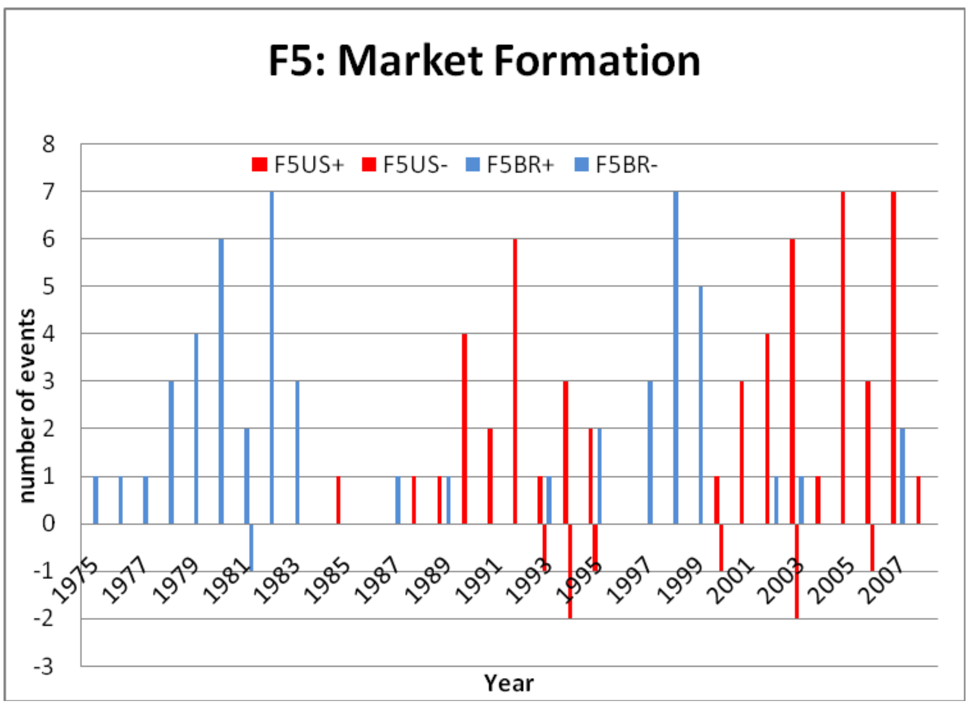

Figure 26: Market Formation (F5) U.S. and Brazil - number of events reporting on ethanol

Reports of events related to market formation (F5) in the U.S. do not take place until 1985, when the Environmental Protection Agency completely bans leaded gasoline. This ruling opened the market for gasohol, a mix of 90% gasoline and 10% ethanol. In the mixture, ethanol substitutes the lead as an anti-knocking additive. Policies stimulating demand of ethanol take place earlier in Brazil. At the onset of the National Alcohol Plan (1975) the Brazilian government mandates the use of ethanol first as a blend with gasoline, then later as a 100% fuel in substitution of gasoline. The second period of strong activity in market formation for Brazil takes place during the late 1990s, the period of deregulation of prices of ethanol, when the Brazilian government stimulates market demand by creating the green fleet, and by mandating blending of ethanol to gasoline. The U.S. boosts market formation activities after the year 2000 through energy legislation and programs mandating growing use of ethanol, and providing tax incentives to ethanol producers. After 2000, the only market formation activity in Brazil is the continuing mandatory blending of ethanol with gasoline.

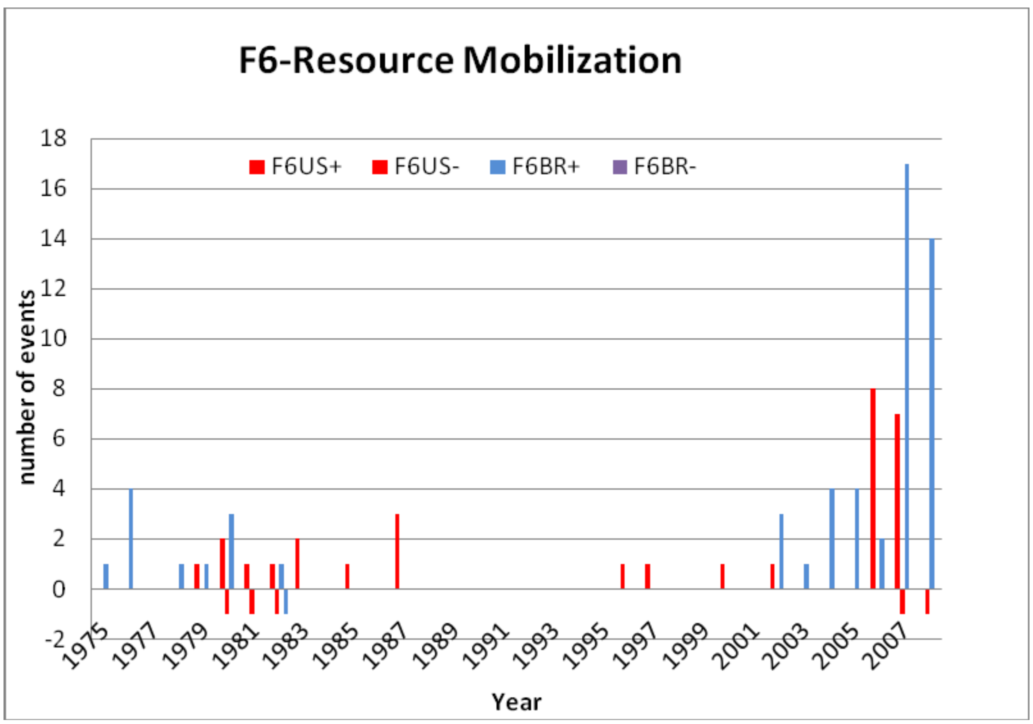

Figure 27: Resource Mobilization (F6) U.S. and Brazil - number of events reporting on ethanol

Like entrepreneurship (F1), resource mobilization (F6) is strong earlier and late in the period of analysis. However, Brazil remains stronger than the U.S. in the beginning and at the end of the period. Like with entrepreneurship, there is very little activity during the 1980s and the 1990s. The data, however, underestimate the large investment in R&D devoted to advanced and cellulosic ethanol in the U.S. since the year 2000.

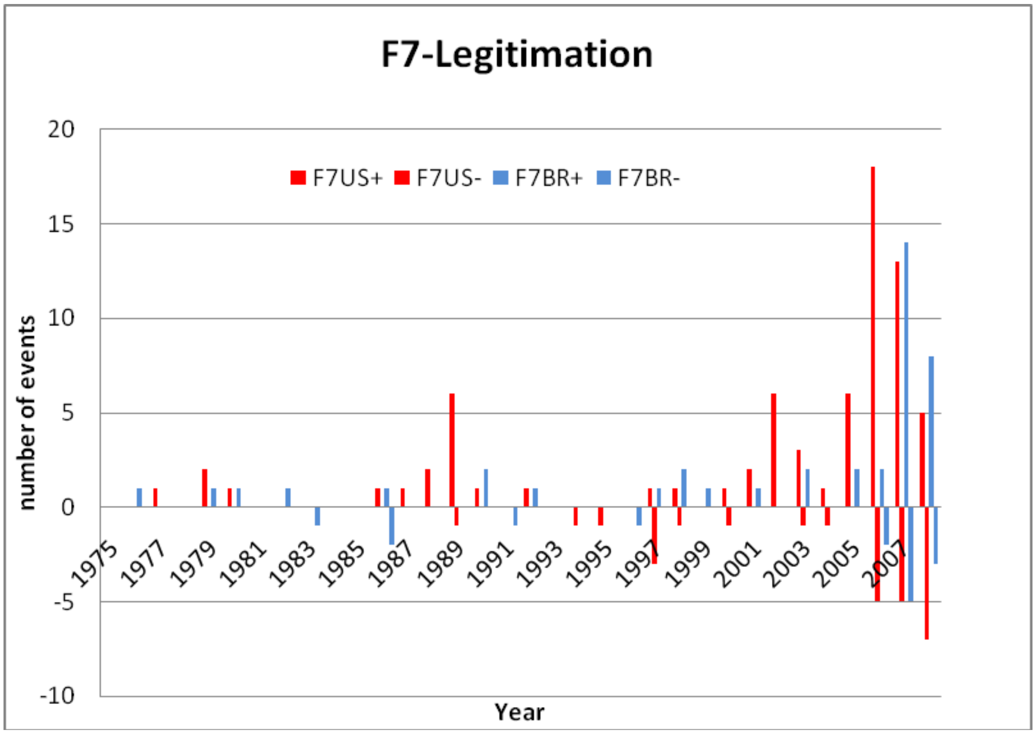

Figure 28: Legitimation (F7) U.S. and Brazil - number of events reporting on ethanol

Loud voices supported the ethanol TIS throughout the years in the U.S. Earlier, there was some action to strengthen and legitimize ethanol, especially to lobby for legislation to approve higher blends of ethanol as a substitute for gasoline during the late 1980s. More recently, the Bush administration started an aggressive program in support of more advanced ethanol, and in support of mandates to consolidate the market of ethanol in the long term. The Obama administration reinforced the policies and the legitimation of biofuels, boosting investments through the American Recovery and Reinvestment Act. Brazil's main strategy is to gain the world market, and the Brazilian ethanol lobby has been vocal to legitimize the Brazilian ethanol as a sustainable technology and international commodity. In the two countries, the ethanol lobbies as well as political forces act more forcefully after the year 2000, when prices of gasoline tend to be higher. See figure 28.

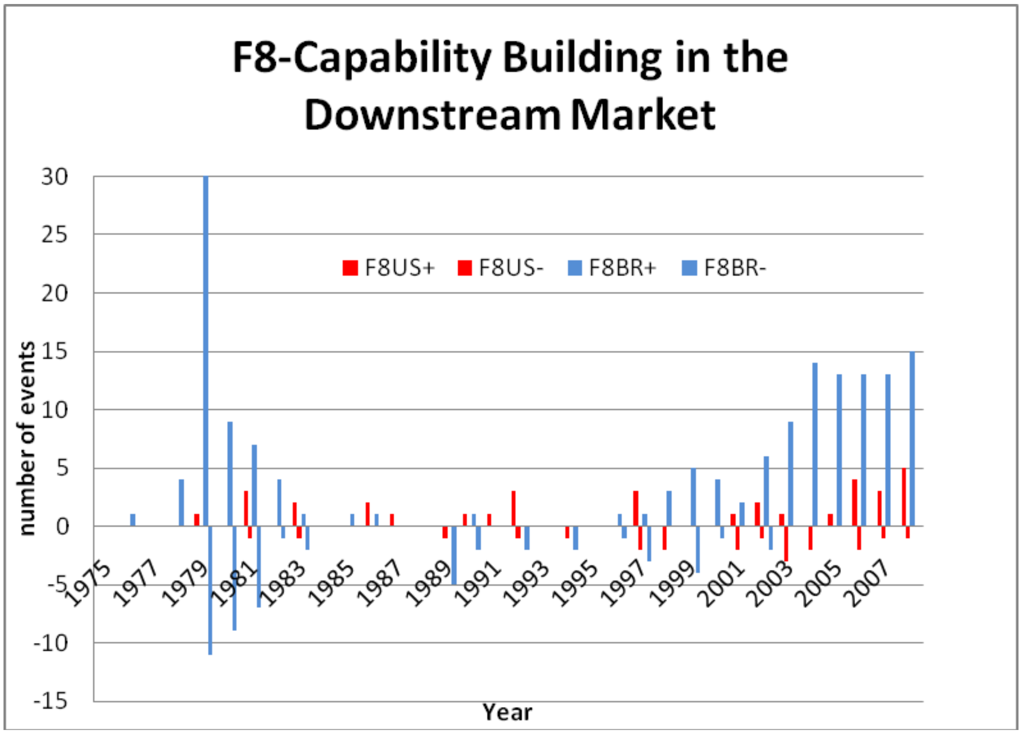

Figure 29: Building of capabilities in the downstream market (F8) U.S. and Brazil - number of events reporting on ethanol

The contrast between the U.S. and Brazil in the function capability building in the downstream market is very telling. Brazil's automobile sector becomes very active during the first Proalcool Plan, when automakers developed car engines capable of running on 100% ethanol. Despite all the problems during the 1990s, a period considered by many as the lost decade of ethanol in Brazil, the knowledge and competence obtained during the first phase in the 1970s and 1980s helped the automakers adapt the flex fuel technology (developed in the U.S. during the 1980s and 1990s) to the Brazilian reality (using engines capable of using gasoline, 100% ethanol, or any mixture of the two). As the narrative story described in more detail, the development of the flex fuel market rebuilt consumer's and investors' confidence in ethanol as a fuel, triggering the successful restart of the ethanol program in Brazil.

The U.S., on the other hand, has had some activity in the downstream market – some minor efforts to develop infrastructure – and some automakers making some steps to boost the E85 program. But despite the growing number of flex fuel vehicles, 99% of them run on gasoline, because of the small number of ethanol pumps in the country[40].

Summarizing

- Brazil is more active earlier on in entrepreneurship (F1), and in knowledge creation (F2). The narrative shows that knowledge creation took place not only in the agriculture and industrial sectors, but also in the automobile sector. By the end of the 1970s, beginning of the 1980s, Brazil was already exploring new engine options capable of running on 100% ethanol. Since the innovation process is cumulative, the earlier start will have important implications for the learning process, in special for "learning by doing".
- Still a military dictatorship, Brazil enjoyed strong government intervention to create a market for ethanol in the beginning of the program. During the deregulation process, the government kept some incentives, the most important being the ethanol blending mandate in the percentage of 20-25%. The successful launch of flex fuel vehicles provided the necessary ethanol demand to boost ethanol production. Brazil keeps mandatory the blending of ethanol into all gasoline in the country. Ethanol market

[40] Only 2,200 of 160,000 gas stations in U.S. have ethanol pumps, and most E85 pumps are located in 10 states that have 20% of vehicles running on ethanol.
http://www.reuters.com/article/idUSTRE61F1OQ20100216 (03/03/2010)

penetration in the U.S. remains dependent on long term mandates (RFS), and will soon face the 10% blend wall[41].

- Like entrepreneurship (F1), resource mobilization (F6) has some minor activity earlier in the period, but most of the activity takes place after the year 2000, with Brazil being more aggressive than the U.S.
- The U.S. is more active than Brazil in lobbying for ethanol, more so after the year 2000 when higher gasoline prices put the issue of alternative fuels high in the American policy agenda.
- The function guidance of research (F4) shows that throughout the innovation trajectory, the Brazilian ethanol has shown ups and downs until the launching of FFVs, which provided the necessary market demand to boost the ethanol program and to reassure stakeholders in the innovation system about the long term prospects of the program. The U.S. is still facing questions over the sustainability of corn-based ethanol, and the corn ethanol industry faces the threat of the blend wall that limits the market. At the same time, the advanced ethanol industry is still working to make its process competitive with gasoline at commercial scale. The low expectation about the technology/industry hampers risky investments necessary to trigger a sustained process of innovation.
- Brazil is significantly stronger than the U.S. in building capability in the downstream market (F8) throughout the whole period. This advantage affected the gap in the overall performance of the ethanol innovation system between the two countries in some ways:
    - In Brazil, FFVs use hydrated ethanol, while in the U.S. consumers fuel FFVs with anhydrous ethanol blended with 15% gasoline. Because hydrated

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[41] The blending limit with gasoline in the U.S. is 10%. The market of ethanol is reaching 10% of the gasoline market, and there are not enough ethanol pumps to boost sales of E85.

ethanol does not require a dehydration step, it tends to be less expensive than anhydrous ethanol. Moreover, Brazilians use ethanol at 100%, which does not require the blending operation with gasoline, as is the case of E85 in the U.S. These structural differences give Brazilians a cost advantage compared to the U.S.;

o Because most FFVs in Brazil use ethanol, engines are tuned to run with ethanol. Therefore, they are designed with higher compression rates, taking advantage of high octane properties and higher energy density of ethanol compared to gasoline. In the U.S., most FFVs run on gasoline, and engines are tuned to run on gasoline;

o In Brazil, sales of hydrated ethanol have substituted gasoline. In the U.S., ethanol has been a complement to gasoline, with a blending limit of 10% authorized by the EPA. As long as ethanol remains a complement, there is the risk of reaching the "blend wall". This affects negatively how investors perceive the business (-F4).

o Throughout the years, with the help of the Brazilian government, automakers in Brazil became participants in the ethanol innovation system. This has not been the case with automakers in the U.S, who through market forces, have developed their business participating more in the gasoline TIS than in the ethanol TIS.

The next two graphs, one for the U.S. and one for Brazil, map all the functions throughout the whole period of analysis. The graphs show the cumulative sum of events for each function in their respective positive and negative sides of the graph. The differentiation between positive and negative functions identifies whether the function contributes or is detrimental to the process of innovation of ethanol. According to the theory, we would like to see a growing trend towards the positive direction, ideally with the largest number of lines going up. We see somewhat a growing trend in the positive side for the U.S., but much more timid than for Brazil. We see guidance of research (-F4) in blue falling down in the negative direction. Brazil has a strong positive start, but has guidance of research (F4) and capabilities in the downstream market (F8) falling down in the negative direction during the 1990s, the years when the ethanol program came to a halt.

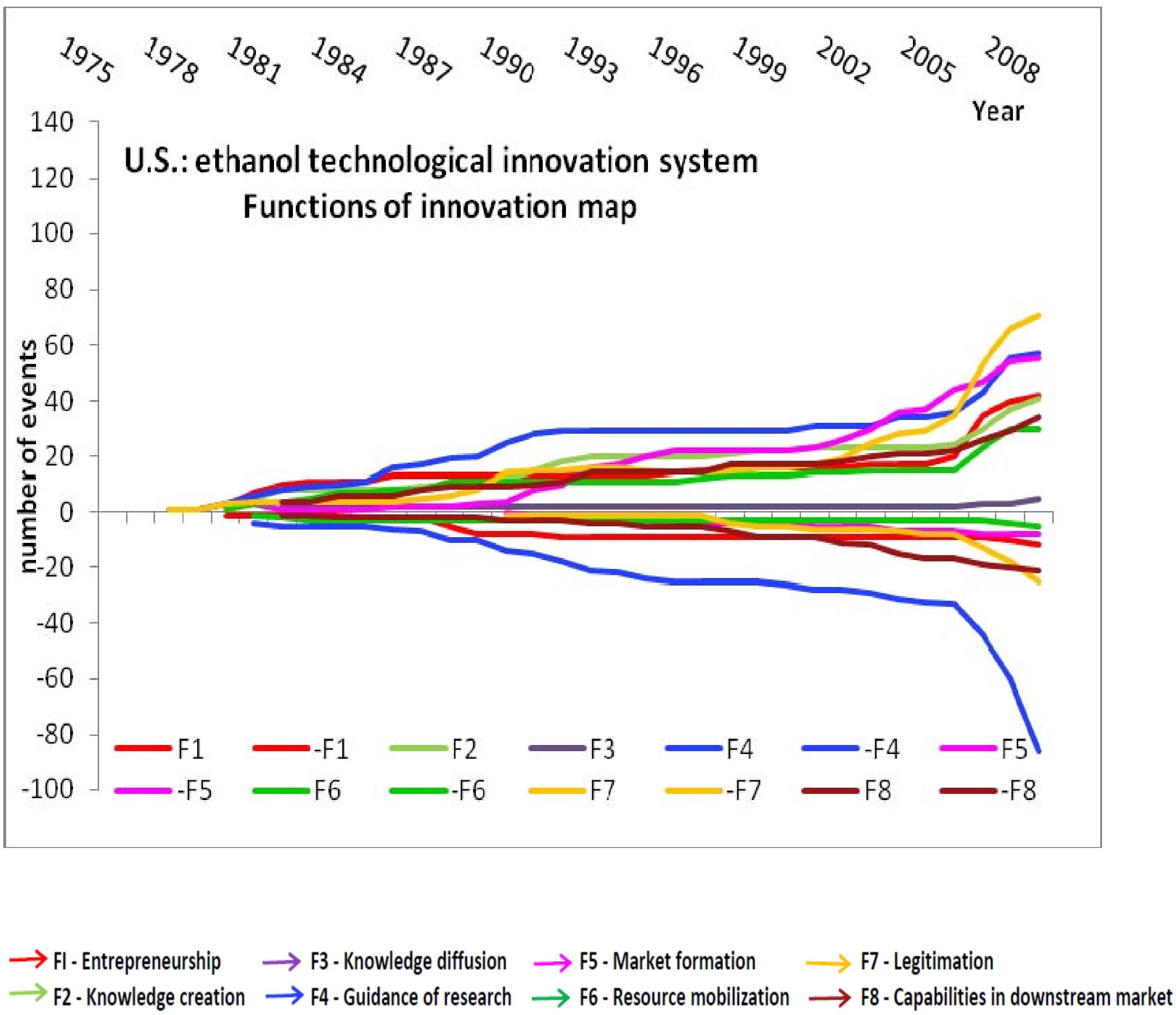

Figure 30: U.S. – Mapping the Functions of innovation

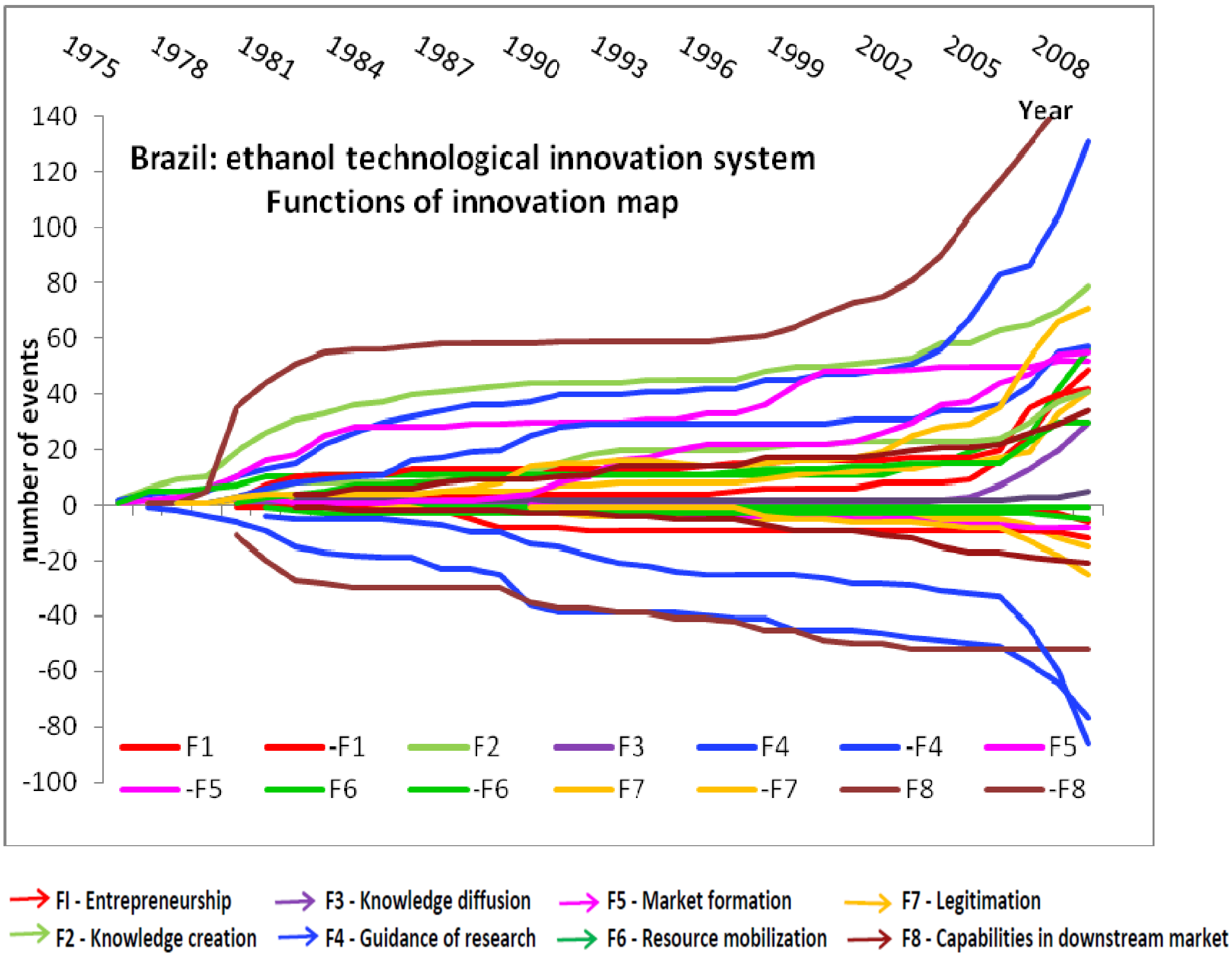

Figure 31: Brazil – Mapping the Functions of innovation

The next graphs show functions individually, by country, and by year. The lines represent the sum of positive and negative values of events for each function by country, for each individual year. This simplification helps compare the pattern of evolution of each function of innovation between the U.S. and Brazil[42]. The graphs in figure 32

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[42] Pearson correlation test, using a significance level alpha=0.05. r = coefficient of correlation

clearly reveal similar trends between the U.S. and Brazil for functions F1 (entrepreneurship), F2 (knowledge creation), F5 (market formation), F6 (resource mobilization), and F7 (legitimation). The correlation between the U.S. and Brazil for guidance of research, F4, is weaker. The negative Pearson correlation confirms that the U.S. and Brazil have trends going into opposite directions, especially after the year 2005, when corn ethanol became more scrutinized for its long term sustainability and impacts in the food and feed markets.

The function capability in the downstream market (F8) shows the weakest correlation between the U.S. and Brazil (0.19), reflecting the contrast between the U.S. and Brazil in how the function building of capabilities in the downstream market influenced the innovation process of ethanol in the two countries. This quantitative result is consistent with the qualitative analysis presented in the narratives. Brazil starts building capability in the downstream market in the late 1970s, early 1980s, when it starts developing the distribution infrastructure and commercialization of cars running on 100% ethanol. Despite the downturn of the ethanol plan during the 1990s, the capability acquired earlier helped the ethanol comeback into consumers' vehicles, this time into flex fuel vehicles with technology adapted to the Brazilian reality and technology. The United States did not start building capability in the downstream market for ethanol until the 1990s, when automakers developed and implemented commercially the flex fuel engines. The new technology, however, has not had a significant impact into the innovation trajectory of ethanol, because most cars have not been able to use ethanol (E85). Most flex fuels (99%) use gasoline, because only few fuel stations offer E85 as an alternative for consumers. As a result, flex fuel engines have not been optimized to run on ethanol in the United States.

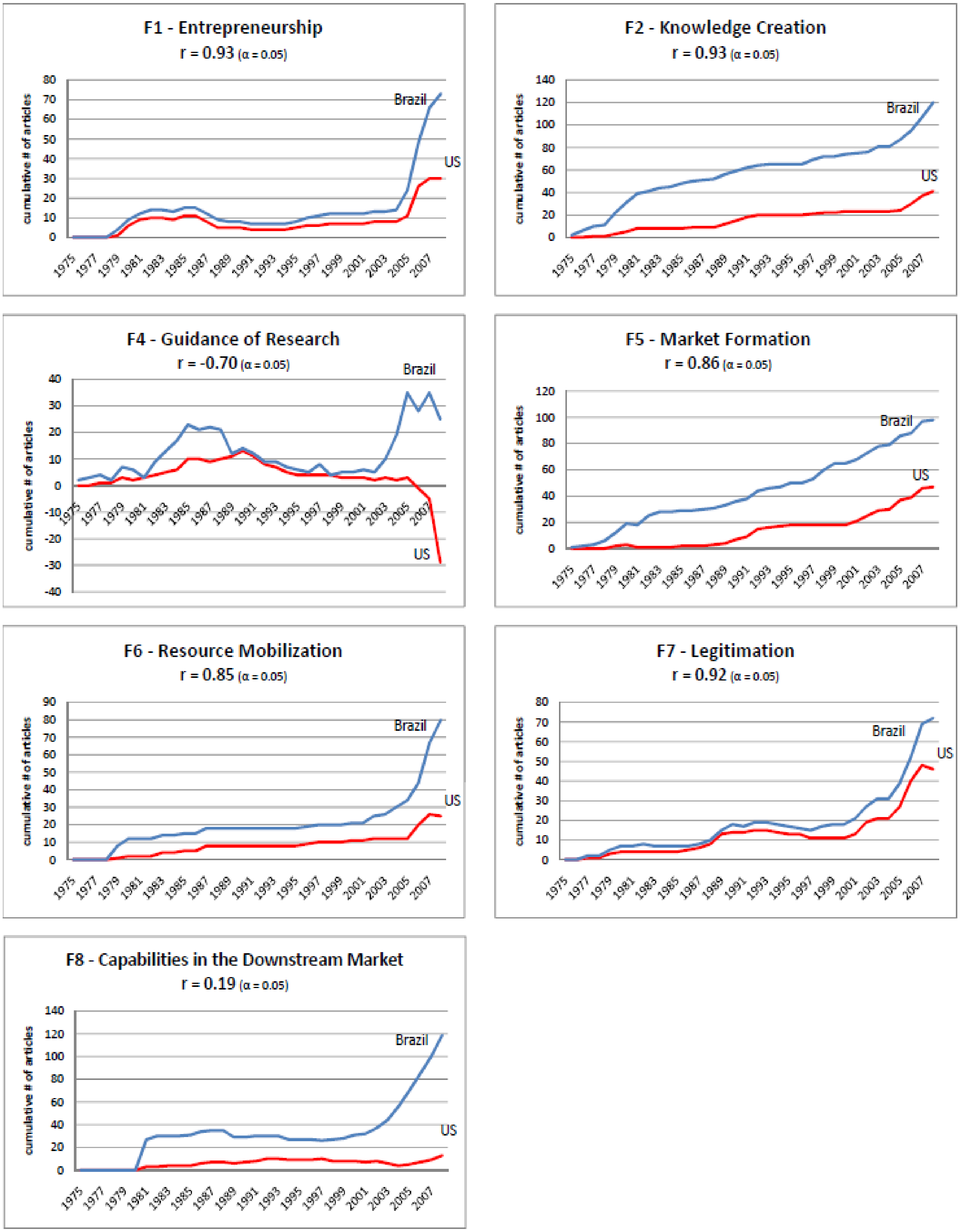

Figure32: Functions of innovation. Comparative analysis, correlation between the U.S. and Brazil (F1, F2, F4, F5, F6, F7). Source NYT, WP, OESP. Elaborated by own author.

CHAPTER 9

CONCLUSIONS AND POLICY IMPLICATIONS

This dissertation explored the innovation dynamics of ethanol in the U.S. and in Brazil from 1975 to 2008. The quantitative and qualitative analyses just presented revealed that the two functions of innovation, Guidance of Research (F4) and Building of capabilities in the downstream market (F8) explain an important part of the differences in the innovation process between the U.S. and Brazil.

Guidance of Research (F4): Guidance of Research is stronger for Brazil than for the U.S. In general, expectations about the Brazilian ethanol have been more positive when compared to the U.S. The graph in figure 32 shows that while Guidance of Research has had an overall positive effect on the innovation process of ethanol in Brazil, it has been detrimental to the innovation of ethanol in the U.S., especially after 2005. The negative correlation indicates trends for guidance of research going into opposite directions. Given the low penetration of ethanol in the gasoline market as a substitute of higher blends, this result suggests that clear policy goals and expectations about the technology play an important role in the innovation trajectory of emerging low carbon technologies such as biofuel ethanol.

Building of capabilities in the downstream market (F8): the study shows significant differences in how the U.S. and Brazil built capabilities in the downstream market to advance their respective processes of innovation. The narratives and the low correlation between the U.S. and Brazil in this function support this conclusion. Taking into account events contributing and detrimental to the innovation process, Brazil has had a much higher positive impact than the U.S. during the last three decades. Brazil started building capabilities early in the period by developing the infrastructure for distribution of ethanol and commercializing ethanol cars during the 1980s. This early experience reinforced the innovation in the upstream market, and helped Brazil regain a successful innovation path after the flex fuel vehicles came to the market in 2003. In the U.S., the development of capabilities in the downstream market was more limited to the development of flex fuel vehicles, without developing proper infrastructure for the distribution of ethanol fuel in the gas stations. The result has been most flex fuel vehicles in the U.S. running on gasoline and not on ethanol (E85). This result suggests that the function building of capabilities in the downstream market proposed in this dissertation is able to explain some of the differences in the trajectories of innovation of biofuel ethanol between the U.S. and Brazil during the last thirty years.

By using the functions of innovation and process analysis, this dissertation answered the following questions:

1.Q What are the differences between the functions of innovation of ethanol in the U.S. and Brazil? How have those differences evolved over time?

The quantitative and qualitative analysis showed the following:

F1

Both countries had a similar number of positive events in entrepreneurial activity. In the U.S, entrepreneurship was more regional and centered in the Midwest in the beginning of the period. In Brazil, the military state was the main entrepreneur, controlling the whole innovation process of ethanol throughout the whole supply chain. Entrepreneurial activity took off after the year 2000 for the two countries: in the U.S, thanks to the Energy Policy Act of 2005 and RFS, which mandated use of ethanol, and in Brazil, thanks to the successful launch of flex fuel vehicles.

F2

The data reveals that knowledge creation in Brazil was more intense than in the U.S. The results do not reflect the American leadership in R&D in cellulosic ethanol, a fact that is supported by data available in international scientific databases. However, since events related to knowledge creation took into account gains in knowledge, skills, and competence in a broader sense, they included the positive experience Brazil had in the development of the engine running on 100% ethanol, and later the development and adaptation of the technology flex fuel. It also took into account improvements in the sugarcane and ethanol technology; and much of those happened through learning by doing. More recently, knowledge creation became more focused on R&D in second generation technology. In the U.S., the data also reflect more commitment towards research after the EPAct2005. At the end of the period, the gap is less dramatic between the two countries.

F4

U.S. and Brazil had a high number of negative events in Guidance of Research. The lack of long term goals and lack of definitions was recurrent throughout the period for the two countries. The data, however, shows Brazil gaining a positive pattern in the function after the beginning of sales of flex fuel vehicles. Brazil has had some bad criticism, in special coming from abroad about the long term sustainability of its program, but overall, it has had a positive balance. The positive Guidance of Research will have a positive influence in future investments and entrepreneurial activity of ethanol in the innovation of ethanol in Brazil. The U.S, on the other hand, has still a negative balance in the late period, and it relies on the future of cellulosic ethanol to regain long term trust for its sustainable future.

F5

Market Formation activities have the same intensity in the two countries. But they take place in different periods of time. Brazil begins earlier, reflecting the strong intervention of the military government in the beginning of the period. In the U.S, activities of Market Formation were first linked to the Clean Air Act Amendments of 1992 and the New Oxygenated Fuels Program, which required oxygenated fuels to cut carbon monoxide pollution in certain areas of the country. The legislation opened the market for ethanol as oxygenate. The Market Formation in Brazil in the late 1990s relate to new mandate programs established by the new democratic government to find new markets for ethanol. After the beginning of FFV sales in Brazil, when prices were deregulated, the government kept the mandatory gasoline blend with ethanol between 20 and 25%. In the U.S., mandates established by EPAct2005 and strengthened by EISA2007 reflect most of the activities to stimulate the American market for ethanol in the late period.

F6

Brazil has twice the number of positive articles reporting events reflecting investments in ethanol than the U.S. However, the data does not take into account a large amount of investments made into cellulosic ethanol, especially after 2000 in the U.S. The data reveals that between the late 1980s and the late 1990s, the years of cheap oil, there was not much investment in ethanol in any country. However, the new millennium brought new priorities, and biofuels came back to the policy agenda as an alternative solution for climate change, energy security, and the volatility in oil prices. Investment activity became intense after 2000. In Brazil, it was stimulated by the positive expectations about the future of ethanol in the country. In the U.S, there was investment euphoria until 2007, but the market did not develop enough infrastructure for distribution and use of ethanol to take in the additional capacity at the speed expected by investors.

F7

The U.S. innovation system has built a strong lobby to advocate publicly for the interests of the industry. The function of legitimation for the U.S. is stronger than for Brazil. This makes sense, because under the dictatorship, the military government had total control to legislate over the innovation process of ethanol in Brazil. Also, a system of corporativism was prevalent in Brazil during the Proalcool program, and a close relationship between the state and the private sector remained strong after the democratic constitution of 1988 (Goncalves Jr, Alves, Shikida, Staduto, & Freire Jr, 2008). With Brazilian ambitions targeting the global market, and criticism affecting negatively the Brazilian industry, the country has now increased efforts to legitimate ethanol as a fuel at home and abroad.

F8

The data reveals the largest gap between the U.S. and Brazil in positive activities of Building of Capabilities in the Downstream Market. The multinational automakers in Brazil joined the Proalcool in the beginning of the period and took advantage of incentives offered by the government to expand the market for automobiles. However, the lack of ethanol led automakers to shift all production to gasoline cars during the 1990s. By the late 1990s, the government promoted again the ethanol car, establishing the green fleet. Thus, function F8 had no activity during the 1990s. Automakers only joined the ethanol TIS again for the launching of the flex fuel vehicle, which happened after 2000. The flex fuel impact in the innovation trajectory of ethanol in the U.S. has had less impact than in Brazil, because no appropriate distribution infrastructure was in place. Moreover, automakers developed FFVs taking advantage of CAFE credits during a time when their main source of profit was to sell large and inefficient vehicles. Because most users of FFVs use gasoline, engines cannot be tuned to maximize the anti-knocking and energy density properties of ethanol, as it is the case in Brazil. Engines are tuned to run on gasoline, negating all benefits of the technology for potential users of E85 (Voegele, 2010).

2.Q Which are the strongest and weakest functions in each country? How do they compare to each other?

According to table 4, the U.S. has made great efforts in legitimizing ethanol as fuel in the U.S. Since the beginning of the period, farmers, and corn producers had the support of legislators who helped advance important legislation for the industry. Some corporations such ADM still make efforts to influence the policy process relevant to the business. It is interesting to note that while Legitimation is the "most positive function" for the U.S., Guidance of Research is the "most negative function" for the U.S., suggesting that the strong ethanol lobby has been acting to counteract the criticism, negative expectation, and lack of policy goals for the ethanol industry in the country (-F4). Eventually, EPAct2005 and EISA2007 clarified policy goals, establishing mandates, and funding R&D. However, the debate over the sustainability of corn ethanol has not done well for the business, and expectations now turn to the timing of commercialization of cellulosic ethanol.

In Brazil, the "most positive function" has been F8 (Building of Capabilities in the Downstream Market). This function brought the innovation trajectory of ethanol into a nice path during the 1980s, but collapsed during the late 1980s and 1990s for a number of reasons. Some of the reasons include bad government planning and management, unforeseen decrease in oil prices, higher sugar prices in the international market, thus creating undersupply of ethanol in the Brazilian market. The function F8 rebounded with the development of the flex fuel technology. Brazilians used the concept developed in the U.S., but adapted to Brazilian conditions, using the knowledge generated during the Proalcool program. Like the U.S., the "most negative function" in Brazil is Guidance of Research. Data shows that the country achieved a sustained innovation path after the launch of flex fuel vehicles. Much of the history of the innovation of ethanol in Brazil has been marked by ups and downs, corruption, lack of policy goals, and very low expectations about the prospects of ethanol as a fuel.

3.Q What are the causal patterns that explain the outcomes of ethanol development for each country over time?

The narratives reveal that until the year 2000, there is not a sustained pattern of innovation in either country. The graphic representations of the evolution of the functions of innovation show that it is only after the year 2000 that there is a building up of functions in the positive side. The narratives also reveal that neither of the countries developed a sustained market for ethanol until the year 2000. After 2000, the U.S entered a positive path with the passage of the Biomass R&D Act (guidance of research F4), creating funds for R&D of advanced biofuels (resource mobilization F6, knowledge creation F2). At the same time, the banning of MTBE as oxygenate raised expectations about market growth of ethanol as an additive (MTBE had 85% of the market at that time). The prospects of more R&D and market expansion of ethanol (guidance of research F4) had a positive impact in productive investments (resource mobilization F6) and entrepreneurial activity (F1). There was a surge of investments and plant constructions in the U.S. However, the investment euphoria did not take long because demand was not large enough to take in additional volumes in the long term. As has already been mentioned, main limitations were the blend wall and lack of pumps selling E85. The lack of capacity in the downstream market would bring financial pains to many investors in the sector (-F8).

Brazil entered a positive path of innovation after the successful launch of the flex fuel vehicles (capabilities in the downstream market F8), generating positive expectations about the ethanol market in the country (guidance of research F4). The flex fuel technology gave the needed flexibility to Brazilian consumers, who were able to choose the fuel at the pump. The timing coincided with larger crops of sugarcane, and low prices of ethanol. For the most part of the time, ethanol was less expensive than gasoline at the pump (prices were not controlled by the government anymore). High expectations drove investments to more production of sugarcane, and ethanol (resource mobilization F6, entrepreneurship F1), keeping the expectations about ethanol innovation high (guidance of research F4), closing the positive cycle of innovation. Given the success of the program, automakers invested to improve the flex fuel technology (resource mobilization F6, knowledge creation F2), taking greater advantage of ethanol properties. Flex fuel sales reached 90% of new cars in Brazil (capabilities in the downstream market F8). The positive cycle remains, setting the ethanol TIS into a sustained innovation path.

The cases of U.S. and Brazil confirm what the literature has already reported previously that Guidance of Research (F4) is a trigger of the innovation process for low carbon technologies. As argued earlier, the expectation about the technology plays a critical role driving decisions of investments in R&D, and production. In the U.S and in Brazil, Guidance of Research (F4) after 2000 had a positive influence in investments in R&D (F2, F6), and in expanded capacity (F1). The same pattern was present in other cases of biomass digestion and biomass co-firing in Germany (Marko P. Hekkert & Negro, 2009; Negro & Hekkert, 2008); biomass gasification and biomass digestion in the Netherlands (Marko P. Hekkert & Negro, 2009); biofuels in Sweden and in the Netherlands (Hillman et al., 2008; Suurs & Hekkert, 2009); and biopower (CHP) in Sweden (Jacobsson, 2008).

The analysis of the new function of innovation proposed in this study, building of capabilities in the downstream market (F8), reveals differences in the innovation trajectory between the U.S. and Brazil. Moreover, as has been described in the narratives, a strong downstream market that works in coordination with the upstream market can play a positive role and accelerate the process of innovation. Brazil's ethanol innovation system began recovering from a decade of no achievements by building capability in the downstream market (F8). The launching of flex fuels vehicles in 2003 was the critical factor for innovation to take off, because ethanol was the main fuel used by flex vehicles' drivers. This indicates that the downstream market was taking part in the TIS trajectory in Brazil, thus driving policy and increasing expectations about the ethanol innovation in Brazil. The knowledge generated during the Proalcool (during the 1970s and 1980s) for the development of the ethanol car was useful to improve the competitiveness of ethanol in the new flex fuel technology. This was not the case in the U.S, where the commercialization of flex fuel vehicles has not influenced the innovation of ethanol. The distribution of fuels in the U.S. is still “locked in” to gasoline, and a large investment is needed to build the necessary infrastructure for the appropriate distribution of E85 through pipelines and in service stations. Government stimulus has not been sufficient to stimulate the private sector. This indicates that the downstream market in the U.S. has not been taking part in the innovation trajectory of ethanol. The figure below illustrates the contrast between the U.S. and Brazil in how their respective functions may act to bridge downstream and upstream market to accelerate the innovation process of ethanol. While in Brazil the downstream market (automobile industry – internal combustion engines) is more connected with the TIS ethanol than with the TIS gasoline, in the United States the downstream market remains more connected with the TIS gasoline.

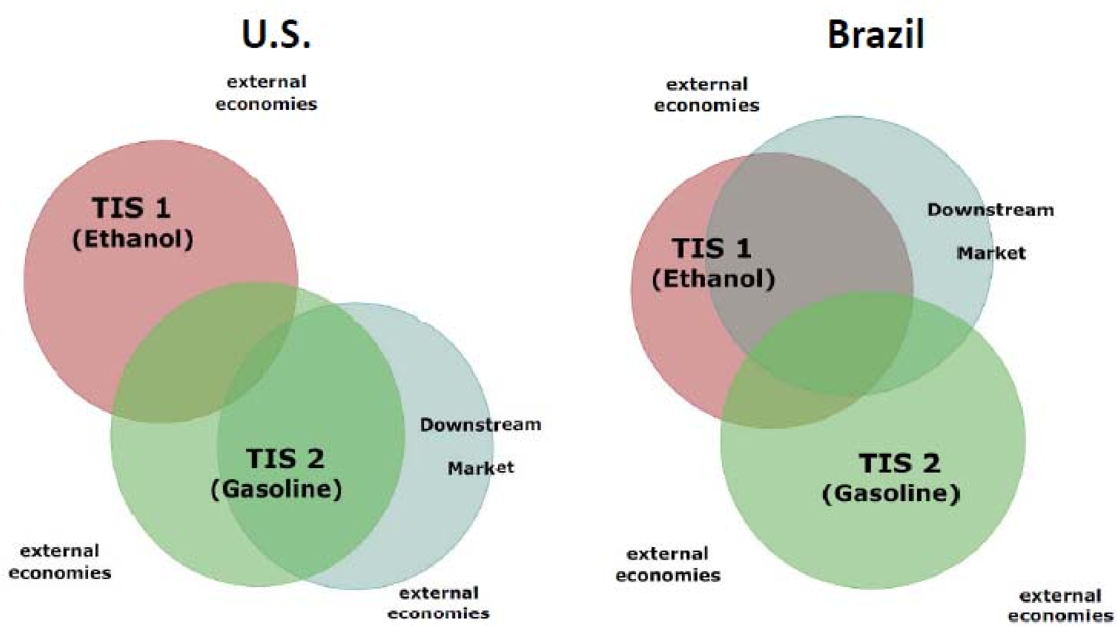

Figure33: Building of capabilities in the downstream market and competing TIS

This study raises some relevant issues for innovation policy:

1. The function of innovation guidance of research influenced innovation trends positively. A strong and positive guidance of research induced innovation, while a weak or negative guidance of research was detrimental to the process of innovation in these cases. This finding has relevant policy implications:

    a. If guidance of research is an inducer of innovation, then it is critical that policy makers set clear policy goals about a technology. Clear policy goals increase expectations about the technology, and decrease the risk that is inherent to the innovation process. It is important that policy makers and advocates supporting the development of the technology maximize information exchange among the participants of the innovation system at all levels, so that goals, needs, and perceptions are homogeneous within the policy community.

2. Still related to guidance of research, the results show that expectations about an emerging technology can induce or be detrimental to the innovation of such technology. The case of ethanol in the U.S. has shown that the negative expectation about corn ethanol (resulting from the food vs fuel debate, and the debate of the long term sustainability of corn ethanol) has been detrimental to the process of innovation of biofuel in general. A specialist in the industry in the U.S. has confirmed this assertion by interview. Advanced biofuels are still considered risky investments. However, the negative perceptions about corn ethanol are not always supported by the facts. As Chapter 3 has claimed, corn ethanol can be produced using modern technologies that are more efficient and less carbon intensive.

a. The results suggest that the U.S. government at the present time should be more aggressive and provide more incentives for plants investing in technologies to produce advanced corn ethanol. It should also inform consumers and other stakeholders about the innovation happening in the 1st generation technology. The creation of a positive expectation is critical until the 2nd generation technology is ready to be on the market. This is particularly true because many investors in cellulosic ethanol are large producers of corn ethanol, like POET, the largest producer of corn ethanol in the U.S.

3. This dissertation also found that the function of innovation building of capabilities in the downstream market induced innovation in Brazil and was detrimental to the process of innovation in the United States. This finding also has important policy implications:

   a. In the case of ethanol in the U.S., it seems that automakers do not have the same motivation to innovate in E85 as they have in combustion engines running on gasoline. This is understandable, since they still operate under a system that functions under “carbon lock-in”. As long as there is not the critical infrastructure to sell E85 to consumers, automakers do not have enough incentives to invest in flex fuel technology. The results suggest that the American government should create incentives for automakers and distributors (oil companies) to join or share more space within the ethanol technological innovation system.

This dissertation analyzed the innovation process of biofuel ethanol in the U.S. and in Brazil, the two largest producers of biofuels in the world. By using a functional approach to explain innovation, it identified two factors playing a significant role in the success of the innovation process of ethanol in these countries. As society becomes increasingly pressed by the challenges of energy security and climate change, it becomes urgent to improve the field of innovation studies with the necessary tools to better measure and assess the innovation of low carbon technologies. The findings presented in this dissertation represent an effort in this direction: an additional contribution to the scholarship of innovation of low carbon technologies.

Appendix A - Functions of Innovation Systems – Codebook

	Function Name	*Definition*	*Code Description*	*Values*
F1	**Entrepreneurial Activities**	Events that reflect growing or diminishing industrial capacity, new projects and plants (Investments will focus on specific plants or projects)	Announcement of new ethanol production plant, or acquisition of plant, expansion of ethanol production.	+1
			Diminishing production, or investment in production, market downturn.	-1
			Ethanol producers file for bankruptcy or industry under financial stress	-1
F2	**Knowledge Development**	Events related to Research, Development, and Demonstration of technologies	Feasibility studies or new projects exploring ethanol	+1
			A new patent on ethanol	+1
			Any research efforts on alternative fuels (alcohols-methanol, butanol)	+1
			Any development (R&D, demonstration, pilot) on advanced biofuels or cellulosic ethanol, or its feedstocks (for example using genetic engineering)	+1
			Feasibility studies using alternative fuels vehicles (AFV), including flex fuel vehicles (FFV)	+1
			Tests of automobiles, buses, or trucks running on biofuels (obs). Biodiesel goes under "context"	+1
	Function Name	**Definition**	**Code Description**	**Values**
F3	**Knowledge Diffusion**	Events related to knowledge networks that promote interaction and exchange of information	Conferences, workshops, meetings, collaborations	+1

F4	**Guidance of Research**	Events that help the selection of technological options, or those related to the enactment of policy targets. They also reflect the expectations about the technological options expressed by the various actors.	Studies generating positive expectation about the technology	+1
			Study reports positive results from debate food vs fuels. Biofuels do not compromise food supply in the long term.	+1
			Positive results from studies about alcohol fuels	+1
			Positive results from using alcohol fuels in racing cars or other automobilist event	+1
			New legislation promoting the use of alternative fuels	+1
			Positive results from car or engine testing ethanol or other alcohol fuels	+1
			Environmental legislation regulating emissions from gasoline; government support to alternative fuels.	+1
			Banning of MTBE as fuel additive (ethanol competitor) or finding MTBE toxic	+1
			Ethanol more competitive than gasoline, E10 or gasohol more competitive than pure gasoline	+1
			Positive market results, profitable ethanol industry	+1
			Conflicting goals in public financing for the new technology or new policy program	-1

			Debate or conflicting interests around the technology, debate over future of ethanol industry	-1
			Negative market results: lower demand or undersupply	-1
			Negative expectations or negative outlook about the technology – based on studies or reports (food vs fuels, water consumption, deforestation, negative energy balance, negative results in tests in cars, engines, etc)	-1
			Alcohol rejected as alternative to comply with legislation for clean fuels	-1
			Sugar is preferred in detriment of alcohol	-1
			Tax cut to oil companies	-1
			Negative results about alternative fuels program (proalcool is criticized based on negative performance)	-1
	Function Name	**Definition**	**Code Description**	**Values**
F5	**Market Formation**	Events that facilitate the market penetration of the emerging technology	Tax breaks to ethanol producers and blenders or any legislation putting a price on carbon from fossil fuels or giving a price advantage to clean technologies	+1
			Mandates in general, for alternative fuels (E85 and E10), alternative fuels vehicles (FFV, AFV). This includes adoption of Renewable Fuels Standards (RFS)	+1

			Legislation or agreement for legislation mandating use of ethanol/biofuels	+1
F6	**Resource Mobilization**	Events related to physical and human investments, be public or private.	Subsidies and investments in general (group of companies or sector)	+1
			Funding for R&D activities or facilities for ethanol and/or green technologies, demonstration plants	+1
			Private investments to buyout ethanol plants	+1
			Loans, or financing for new plants or increased capacity for ethanol, feedstocks, and distribution (pumps in service stations)	+1
			Early stage funding of alternative fuels technology ventures	+1
			Government and private funding for alternative fuels vehicles and infrastructure	+1
			Government and private investments in education on the technology	+1
			Rejection of financial support and cutbacks in investments	-1
			Delay in investments	-1
			Decreased funding or lack of funding for R&D on ethanol and green technologies	-1

	Function Name	Definition	Code Description	Values
F7	**Legitimation**	Events related to lobbies, coalitions (interest groups, NGOs, industry associations) or political forces (congressional and executive leaders)	Lobbying (advocating publicly) in favor of developing or complementing the technology.	+1
			Ethanol strong, high visibility in the policy agenda. Law makers support legislation for market expansion of ethanol	+1
			Public presidential or political support for ethanol and alternative fuels or vehicles, including cellulosic ethanol	+1
			Ethanol supporters lobby for higher blends of ethanol in gasoline	+1
			Lobbying for certification of product to comply with sustainability standards	+1
			Car makers advocate for more distribution infrastructure (pumps) on high blend ethanol	+1
			Lobbying against the technology, alternative vehicle fuels	-1
			Lobbying against alternative fuels (biofuels): food vs fuel, deforestation	-1
			Critics lobby against the ethanol program	-1

	Function Name	Definition	Code Description	Values
F8	**Building of Capabilities in the Downstream Market**	Events that reflect the development of capabilities in the distribution and in the automobile segments	Start or increase in ethanol (E85) or ethanol blend (E10) distribution; labeling of gasoline with ethanol	+1
			New cars in the market that can run on alternative fuels; increased production of ethanol cars	+1
			Tax incentives for cars running on ethanol	+1
			Decreased production/sales of ethanol cars	-1
			Lack of pumps to supply ethanol to the market; most AFV running on gasoline	-1
			Illegal use of ethanol by consumers	-1
			Legislation (loophole) increase production of FFV SUVs that end up running on gasoline	-1
			Sale problems with ethanol cars (because of technical issues) Consumers cannot find ethanol cars	-1

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